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Power Plant Cooling System Water Consumption and Nonwater Impact Reports

United Engineers and Constructors, Inc.
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Prepared for

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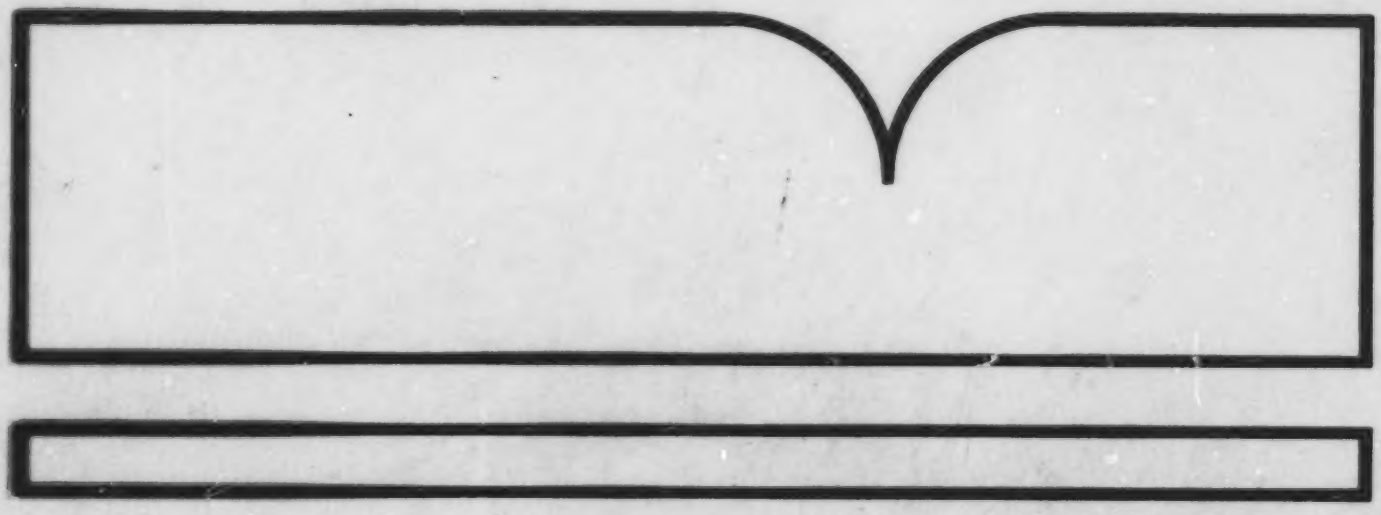

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EXECUTIVE SUMMARY FOR POWER PLANT COOLING SYSTEM WATER CONSUMPTION AND NONWATER IMPACT REPORTS

by

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16. ABSTRACT The report is an executive summary of three studies performed to aid EPA in assessing water consumption and other nonwater quality environmental impacts of cooling systems used by the steam-electric generating industry. The introduction is followed by a summary and major conclusions from the three reports; important details and data serving as bases for the major conclusions are condensed separately, one section per report. The two reports on water consumption agree that the Leung-Moore model satisfactorily predicts evaporation rates of evaporative cooling towers. Versar found that this model predicted evaporation rates at baseload plants witnin + or - 15% of material balance values based on plant data. UEandC addressed the Harbeck and Brady models for predicting evaporation rates from cooling ponds, but (using available data) could not reach a definite conclusion on which model predicted evaporation more closely. Comparing predictions from five models, including the Harbeck and Brady models, Versar concluded that the Harbeck-Koberg-Hughes and Meyer models predicted evaporation rates for five of six cooling pond studies within + or - 15% of material balance values and appear suited to preliminary studies. UE-andC concluded that limited data precluded general conclusions on drift effects from saltwater cooling towers, but that significant impact is not anticipated.

17. KEY WORDS AND DOCUMENT ANALYSIS		
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ABSTRACT

This executive summary contains salient features of three studies performed by United Engineers & Constructors Inc. (UE&C) and Versar, Inc. to aid EPA in assessing water consumption and other nonwater quality environmental impacts of cooling systems used by the steam-electric generating industry. After an introduction followed by a summary and major conclusions from the reports, important details and data serving as bases for major conclusions are condensed separately in a section for each report.

The two reports on water consumption agree that the Leung-Moore model satisfactorily predicts evaporation rates of evaporative cooling towers. Versar found this model predicted evaporation rates at baseload plants within ±15 percent of material balance values based on plant data. UE&C addressed the Harbeck and Brady models for predicting evaporation rates from cooling ponds and using available data could not reach a definite conclusion on which model predicted evaporation more closely. Comparing predictions from five models, including the Harbeck and Brady models, Versar concluded that the Harbeck-Koberg-Hughes and Meyer models predicted evaporation rates for five of six cooling ponds studied within ±15 percent of material balance values and appear suited to preliminary studies. UE&C concluded that limited data precluded general conclusions on drift effects from saltwater cooling towers but that cooling tower drift and deposition apparently do not increase ambient salt loading to an extent that a significant impact has been observed or is expected. Similarly, the effects of wet cooling tower and stack plume interactions on acid rain formation and deposition could not be established from available information.

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SECTION 1

INTRODUCTION

Effluent guidelines for the steam-electric generating industry, point source category, were finalized by EPA in October 1974. Subsequently, the utility industry sued the Administrator regarding certain of the promulgated guideline provisions. In July 1976, the U.S. Fourth Circuit Court of Appeals ruled in favor of the plaintiffs concerning their contentions that water consumption, costs, proven technology for saltwater cooling towers, and other water-related issues were inadequately addressed and that the information provided by EPA was insufficient to justify the established guidelines. Later, the entire set of thermal guidelines was remanded by the Court to EPA for its reconsideration.

Three studies were performed by two contractors to assist EPA's Effluent Guidelines Division in addressing the water consumption and non-water quality environmental impacts of cooling system options available to the steam-electric generating industry. Reports for these studies, listed below, addressed issues which the court instructed EPA to consider.

1. Water Consumption and Costs for Various Steam Electric Power Plant Cooling Systems (EPA-600/7-78-157) by M. C. Hu, G. F. Pavlenco and G. A. Englesson. United Engineers & Constructors Inc. (designated as the first UE&C study).

2. Nonwater Quality Impacts of Closed-Cycle Cooling Systems and the Interaction of Stack Gas and Cooling Tower Plumes (EPA-600/7-79-090) by G. A. Englesson and M. C. Hu, United Engineers & Constructors Inc. (designated as the second UE&C study).

3. Comparison of Model Predictions and Consumptive Water Use of Closed Cycle Cooling Systems (EPA-600/7-78-206) by Jerome B. Strauss, Versar, Inc. (designated as Versar study).

The results of these reports are summarized in this Executive Summary to facilitate easy access to the salient features contained in these reports. The major conclusions are presented in Section 2, along with a summary which provides an overview of the methodologies, data bases and conclusions of the three reports. The important details and data which provide the basis of the major conclusions drawn in the three reports are condensed in separate sections, one for each report. The references cited in each section are listed at the end of the section.

SECTION 2

SUMMARY AND CONCLUSIONS

The first UE&C study(1) compiled, reviewed and evaluated available post-1973 information to assess the state-of-the-art on the following subjects: (a) consumptive water use of various open and closed cooling systems used by moderate and large capacity steam-electric generating stations in the United States; (b) costs of cooling system alternatives; (c) availability of water for all uses and in particular for power plant water heat rejection in the various areas of the U.S.; and (d) impact of regulatory guidelines on consumptive water use in the United States.

The second UE&C study(3) compiled, reviewed and evaluated the available post-1973 information to assess the state-of-the-art on the following non-water quality impacts of cooling towers: (a) drift and salt deposition from saltwater cooling towers and its environmental impacts; (b) weather modifications resulting from cooling tower plumes; and (c) acid precipitation and its environmental impacts resulting from cooling tower plume and stack gas interactions.

The Versar study(2) dealt with water evaporation and consumption of power plant cooling systems and evaluated six simple generic evaporation prediction models, one for cooling towers and five for cooling ponds/lakes using field data provided by twelve utilities. Also evaluated in the study is a regional comparison of evaporation rates of cooling towers and cooling ponds/lakes with the objective of determining which of the two cooling system types is more water consumptive in terms of evaporation only.

The major findings and conclusions of the UE&C and Versar studies will be discussed below according to the topics dealt with in these three studies. The reports of these studies are also summarized separately in Sections 3 through 5 to provide important details and data from which the aforementioned conclusions were drawn.

WATER CONSUMPTION OF POWER PLANT COOLING SYSTEMS(1,2)

The topic of water consumption* of various cooling systems is the sub-

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* Definition of Water Consumption: In the UE&C study, the water consumption of a power plant cooling system is defined as that portion of the water removed from and not returned to the surface water resources of a given area. In the Versar study, the water consumption is implicitly defined as evaporation only. Both definitions have been used in previous water consumption studies.

ject of both the Versar study and one of the four topics of the first UE&C study; the following discussion covers the results of both studies.

The literature review conducted in the first UE&C study revealed that comprehensive calculations of water consumption requirements of major cooling system alternatives in all the water resources regions were performed in three studies(4,5,6); the review found only one field study on a closed cycle cooling pond was reported in the literature(7). Preliminary results from the first phase of the concurrent Versar study(8) using unpublished field data supplied by utilities were also reviewed.

The three analytical studies include two by Espey, Huston and Associates, Inc. (EH&A)(4,5) and one by Hanford Engineering Development Laboratory (HEDL)(6). The predicted water consumption rates obtained by the EH&A and HEDL studies were calculated using water consumption equations which include some or all of the following terms: (a) forced evaporation loss; (b) natural evaporation loss; (c) blowdown; (d) uncontrolled release such as seepage, overflow, drift loss, etc.; (e) local runoff inflow into the ponds/lakes or impoundments; and (f) direct precipitation onto the ponds/lakes or impoundments. Forced evaporation loss is specifically attributed to the cooling process, and natural evaporation exists whether the power plant is operating or not.

The major differences between the two EH&A studies and the HEDL study are in the following areas: (a) the models used to calculate the cooling tower and cooling pond evaporation rates; (b) the assumptions on the cooling tower blowdown rate as a percentage of the tower evaporation rate; and (c) the assumption on the amount of precipitation which may be credited as local runoff to a pond/lake or impoundment.*

UE&C did not reconcile the aforementioned differences when making comparisons and evaluations of the results obtained by EH&A and HEDL, since the purpose of the UE&C study was to assess the state-of-the-art. The results were adjusted only to correspond to the same heat rejection rate (i.e., the heat rejection rate for a 1000-MWe fossil-fueled plant with 36% plant thermal efficiency and 80% capacity factor) and to the same engineering units.

The single field study reported in the literature on a closed-cycle cooling pond(7) did not provide measured water consumption rates. The study concluded, however, that the Meyer model predicts pond evaporation rates in excellent agreement with field measurements obtained in the same study. With respect to the first phase of the concurrent Versar study(8), a complete assessment could not be made by UE&C because of the preliminary nature of the results. The final report(2) of the Versar study is summarized in this report.

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* According to Versar(2), the use of a rainfall runoff credit term in determining water consumption of a cooling system can lead to a significant decrease in predicted water consumption rates based solely on evaporation rates. The credit term represents evapotranspiration by vegetation and water retention by soil.

The major conclusions drawn in the first UE&C study with respect to cooling system water consumption and evaporation rates are as follows:

1. The two cooling tower evaporation prediction models (Leung-Moore(9) and Winiarski(10)) used by EH&A and HEDL give comparable results.

2. The two evaporation rate prediction models for cooling ponds/lakes (Harbeck model*(11) used by EH&A vs. Brady model(12) used by HEDL) give disparate results, the rates predicted by Brady model being consistently much higher than those given by the Harbeck model.**

3. Because of the disparity among the predicted cooling ponds/lakes evaporation rates and the unavailability of consistent sets of field data, a definitive conclusion cannot be drawn as to which of the two models, Harbeck or Brady, gives more accurate results. Consequently, there is an urgent need for a comprehensive program to perform field measurements for verification and calibration of the available models. The ultimate goal of the suggested program is to define a generic cooling ponds/lakes model with semi-empirical correlations identified on a region-by-region basis.

4. A definitive conclusion cannot be drawn as to whether a cooling tower or a cooling pond is more water consumptive on a general basis.

The major purpose of the Versar study(2) was to verify evaporation rates calculated by the models with those determined from material balances using field data provided by the utilities. Another stated major purpose of the Versar study was to compare water consumption rates of cooling towers and cooling ponds/lakes on a regional basis. In the actual analysis, Versar compared only the evaporation rates of the two types of cooling systems and considered that this also represents the comparison of water consumption rates of these cooling systems.

Versar acquired from twelve utilities the field data for 15 wet cooling tower systems and 8 cooling ponds. The cooling towers were designed and operated as "blowdown returned" and the cooling ponds/lakes were built specifically for power plant waste heat rejection (single purpose ponds/lakes). It is important to note that the field data provided by the utilities were generally incomplete and Versar had to estimate the missing data required for the evaluation. Versar indicated that the estimations had been done on a consistent basis with the best information available(2).

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* Referred to as the "Harbeck nomograph" in the Versar study(2) and Section 4 of this report.

** Versar(2) indicated the Brady model to underpredict water consumption relative to material balances for the ponds/lakes studied but generally to a lesser extent than the Harbeck model.

The major conclusions drawn in the Versar study concerning water evaporation and water consumption rates of cooling towers and cooling ponds/lakes are summarized as follows:

1. For cooling towers (blowdown returned and no makeup impoundments), the predicted evaporation rates by the Leung-Moore model(9) are in good agreement with those determined from material balances (within ±15%).

2. For cooling ponds/lakes, the Harbeck-Kobert-Hughes model(13) (Lake Colorado City) and Meyer model(13) generally give predictions within ±15% of the material balance results; the Brady model(12,13), Harbeck model(11), and Marciano-Harbeck model(13) (Lake Hefner) give consistently lower evaporation rates than the material balance values.

3. Cooling ponds/lakes are generally more water consumptive than cooling towers.

4. The satisfactory comparison of the cooling tower evaporation rates predicted with the Leung-Moore model with material balance values developed using field data, supplemented with estimations where needed to complete the evaluation, suggest that this model can adequately be used for estimating cooling tower evaporation rates.

5. Comparisons of the evaporation rates predicted with the five cooling pond/lake models and the results determined from material balances developed using field data, supplemented with estimations where needed to complete the evaluation, indicate that predictions from the Harbeck-Koberg-Hughes model and the Meyer model are preferable over the other models for estimating cooling pond/lake evaporation rates.

COOLING SYSTEM COSTS(1)

The first UE&C study compiled cost estimates of various cooling system alternatives designed for operation in different water resource regions. The results indicate that:

1. There is no discernible trend of capital costs either by regions or by types of cooling system.

2. With respect to total evaluated costs (sum of capital and capitalized operating costs), the observed cost trend for a specific plant generally remains as expected: dry cooling has the highest cost, once-through cooling has the lowest cost, and conventional closed-cycle cooling systems including wet/dry tower systems lie between the two extremes.

3. The economic impact of the use of dry tower cooling to conserve water may be significantly reduced by the use of wet/dry tower cooling. When water is available, however, wet

tower cooling will continue to be the economic choice under most circumstances.

WATER AVAILABILITY FOR STEAM-ELECTRIC AND OTHER USES(1)

Water availability data were reviewed and evaluated in the first UE&C study. An assessment was made, however, solely on the basis of the results obtained in a comprehensive study performed by the United States Water Resources Council and completed in 1978(14). The major conclusions are:

1. There is insufficient water in most of the 18 water resource regions under dry year conditions to satisfy all users at current and projected rates of use. This water shortage situation is particularly critical in the Southwest.

2. Relative to the total water consumption, the percentage consumption for steam-electric generation was 1.23% in 1975 and is estimated to be 2.1% in 1985 and 7.22% in the year 2000.

3. The greatest potential for consumptive water use savings lies in the agricultural sector. Since this sector is the largest water consumptive user in most regions, substantial water savings can be obtained with only small percentage reductions in this user category.

REGULATORY GUIDELINES AND THEIR IMPACT ON CONSUMPTIVE WATER USE(1)

To determine the availability of water from a certain water body for consumptive use by power systems, it is first necessary to examine the laws and regulations that govern water allocation and use. This is because the right to the use of water from a water body is the first determinant as to the water availability for a particular use, even though water may be physically available. The review performed in the UE&C study has indicated that there is no simple way to classify all the different laws and accompanying rules and regulations because they vary widely from state to state. An attempt, however, was made to identify the relevant federal authorities and major legal constraints on the availability of water which are contained in federal statutes, treaties, water rights policies and state laws.

COOLING TOWER DRIFT AND ITS ENVIRONMENTAL IMPACTS(3)

A major concern of using saltwater or brackish water cooling towers is whether the drift from these towers will produce significant environmental impacts, especially to the biota in the vicinity of the towers. An assessment of the potential environmental impacts on biota should include determination of the following items:

1. The naturally occurring salt deposition rates and the atmospheric salt concentrations in the vicinity of the tower.

2. The total salt deposition rates and the atmospheric salt concentrations that result when the tower is in operation.

3. The salt concentration levels in vegetation before and after the cooling tower is in operation.

4. The salt tolerance of each indigenous species of biota.

5. The cumulative effects of salt load on biota.

The information concerning the aforementioned items was compiled and evaluated in the UE&C study. The review has indicated that there are very little actual data available to permit a conclusive determination of the environmental impacts of drift from saltwater cooling towers. On a qualitative basis, however, the following conclusions may be drawn:

1. Cooling tower drift and salt deposition apparently do not increase ambient salt loading to the extent that a significant impact has been observed or is expected. Field data from the operational natural draft cooling towers at the Chalk Point and B. L. England stations indicate that, although drift and its deposition from cooling towers may be significant within the immediate region of a power station, contributions from cooling towers beyond one kilometer may be inseparable from the natural salt loading of the local region.

2. The degree of salt injury to biota from cooling tower drift and salt deposition cannot be firmly determined using presently available data.

WEATHER MODIFICATION BY COOLING TOWER PLUME(3)

The concerns of weather modification by cooling tower plume include: (a) enhancement of the frequency and intensity of fogging and icing, (b) cloud enhancement, and (c) precipitation. The major conclusions drawn from the information compiled are as follows:

1. Field observations on the fogging and icing from natural draft cooling towers suggest that these effects are not significant environmental problems. At most, only a few millimeters of ice has been observed to accumulate on surrounding structures, while fogging from natural draft towers has not been observed under a variety of meteorological conditions. Fogging and icing from mechanical draft towers have been observed, but the tower design significantly affects the probability that the plume will intersect the ground.

2. Precipitation and cloud enhancement by cooling tower plumes have been insignificant although they have been observed in a few cases. Previous studies have indicated that precipitation and cloud enhancement for any sector downwind from a tower are increased by only a few percent.

COOLING TOWER PLUME AND STACK GAS INTERACTIONS(3)

The presence of wet cooling towers, especially large hyperbolic natural draft cooling towers, at fossil fuel-fired steam-electric generating stations raises the possibility that the cooling tower plumes will interact with the combustion gases emitted from the facility's stacks. The commingling of a cooling tower plume with a stack plume, which contains high concentrations of sulfur oxides, nitrogen oxides and fly ash in addition to carbon dioxide and water vapor, can enhance the formation of acid mist in the atmosphere. The presence of acid mist may be evident as increased concentrations of aerosols and fine particulates containing sulfates and nitrates in the commingled plume, acid rainfall, and reduction in atmospheric visibility.

The major conclusions concerning cooling tower plume/stack gas interaction are as follows:

1. There is no mathematical model for predicting acid precipitation due to cooling tower plume/stack gas interaction.

2. Neither the enhancement of acid precipitation nor the resulting environmental impacts due to cooling tower plume/stack gas interaction have been observed in the field.

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SECTION 3

SUMMARY OF UE&C REPORT: WATER CONSUMPTION AND COSTS FOR VARIOUS STEAM ELECTRIC POWER PLANT COOLING SYSTEMS

GENERAL DESCRIPTION

The subject study(1) compiled, reviewed and evaluated available information and assessed the state-of-the-art on the following subjects: (a) water consumption rates of various open and closed cooling systems used by moderate and large capacity steam-electric generating stations in the U.S.; (b) costs of cooling system alternatives; (c) the estimated availability of water for all uses, and, in particular, for power plant water heat rejection in the various regions of the U.S.; and (d) the impact of regulatory guidelines on consumptive water use in the U.S.

The primary objective of the study was to better understand the water consumption aspects of power plant cooling systems as they may impact water availability for power generation and other uses. The literature search included papers and reports from both public and private sources published since 1973.

WATER CONSUMPTION* RATES OF COOLING SYSTEMS

The literature review on water consumption revealed that two reports by Espey, Huston and Associates, Inc. (EH&A)(2,3) and one by Hanford Engineering Development Laboratory (HEDL)(4) contained comprehensive calculations of water consumption requirements of all the major cooling system alternatives for all eighteen water resource regions in the conterminous United States as shown in Figure 3.1. Only one field study on a closed-cycle cooling pond was found in the literature and reviewed. Preliminary results from the first phase of the concurrent Versar study(5) using unpublished field data supplied by utilities were also reviewed.

The cooling system alternatives considered in the EH&A and HEDL studies included the open cycle once-through cooling system and the closed-cycle cooling tower and cooling pond/lake systems; the emphasis of these studies was on the latter systems. A cooling tower was classified as: (a) a tower with or without a supplemental water reservoir for makeup supply, and (b) a tower

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* Definition of Water Consumption: The water consumption of a power plant cooling system is defined as that portion of the water removed from and not returned to the surface water resources of a given area.

with its blowdown retained for on-site disposal or a tower with its blowdown returned to its water resource. A cooling pond was classified as either a single purpose pond or a multi-purpose pond. The former refers to a man-made pond used primarily for power plant cooling with other uses being incidental to its construction, and the latter refers generally to a natural pond used for power plant cooling and other purposes such as recreation and flood control.

The water consumption rates of the aforementioned cooling systems are calculated by equations which may include some or all of the following water consumption terms as appropriate for each cooling system: (a) forced evaporation loss; (b) natural evaporation loss; (c) blowdown; (d) uncontrolled release such as seepage, overflow, drift loss, etc.; (e) local runoff inflow; (f) makeup water; and (g) precipitation impingement onto the cooling water surface. Forced evaporation loss is specifically attributed to the cooling process whereas natural evaporation exists whether the power plant is operating or not. Of these terms, the evaporation loss is the major component for calculating cooling system water consumption rates. It can be calculated with semi-empirical models simulating the operating behavior of various cooling systems.

The major differences between the EH&A studies and HEDL study, which provided the bulk of the calculated water consumption rates reported in this UE&C study, are in the following areas: (a) the models used to calculate the cooling tower and cooling pond evaporation rates, (b) the assumption on the cooling tower blowdown rate as a percentage of the tower evaporation rate, and (c) the assumption on the amount of precipitation which may be credited as local runoff to a pond/lake or impoundment. The details of these differences are summarized in Table 3.1.

A brief description of the evaporation prediction models used by these studies is given below.

Evaporation Prediction Models

1. Cooling Tower Models

An evaporative or wet cooling tower is a device which cools hot water by heat exchange at the air-water interface. The process is primarily based on evaporation (latent heat of vaporization is absorbed by evaporating some water from the cooling liquid) with a small portion of sensible heat transfer. Because both the air and water flows are channeled through the tower, the physical process involved in the tower operation can be easily modeled to give reasonably accurate predictions of the evaporation rate. In cooling towers, the natural evaporation is negligible and the forced evaporation is dominant.

The EH&A studies(2,3) used the Leung-Moore model(6) in the form of nomographs for calculating tower evaporation rates, given the tower heat rejection rate, wet bulb temperature, relative humidity and elevation. The HEDL study used the Winiarski model(7) which involves solving the Merkel's equation to obtain the tower performance and then using the performance data

to calculate the evaporation rate.

2. Cooling Pond Models

Heat dissipation from the pond surface is accomplished through evaporation, convection, conduction, and radiation. It is highly dependent upon local meteorological conditions (solar radiation, dry bulb temperature, relative humidity or dew point, wind speed and cloud cover).

Determination of the evaporative loss of a cooling pond is a considerably more complex task than it is in the case of a wet cooling tower. This is because quantitative estimates of evaporation for cooling ponds involve many parameters, which make the modeling difficult. There are two basic approaches for estimating the forced evaporation from cooling ponds. One is called the energy budget method and is based on the First Law of Thermodynamics. This method accounts for all incoming, outgoing and stored energy at the pond surface layer and enables the calculation of the energy available for evaporation. The other is called the mass transfer method and is based on the Law of Conservation of Matter. A number of models have been developed based on these approaches. The Harbeck model(8) based on the energy budget approach was used by EH&A, and the Brady model(9) based on the mass transfer approach was used by HEDL.

The Harbeck model is represented by a nomograph which gives the ratio of the heat energy input used for forced evaporation to the total heat energy input to the pond/lake as a function of pond water surface temperature, with the two-meter wind speed as the only parameter. (Thermal loading of the pond, that is, heat rejection rate per unit pond surface area, need not be specified.) According to Harbeck, who developed the model, the pond water surface temperature required for the application of the nomograph can be considered approximately equal to the air temperature above the pond. Harbeck(8) states that in areas where ice cover does not occur, the average annual water surface temperature is usually slightly lower than the average annual air temperature because of the cooling effect of natural evaporation. The addition of heat by a power plant may cause the water surface temperature to more nearly equal the air temperature, unless the thermal load is large relative to the size of the lake. Harbeck also states that if large air-water temperature differences exist, the procedure using his nomograph becomes of questionable value* because of probable errors in the conducted energy term of the energy budget equation.

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* In the two studies(2,3) reviewed by UE&C, EH&A used air temperatures as pond water surface temperatures when applying the Harbeck nomograph to calculate forced evaporation rates of cooling ponds. No analysis was given concerning the validity of this assumption when high thermal loading ponds are considered in which large air-water temperature differences potentially exist. In responding to this question raised in the UE&C report after it was published, EH&A performed an analysis which was documented in an unpublished memorandum. EH&A states that its analysis shows that the "Harbeck nomograph is a viable means of estimating forced evaporation for a cooling pond even at load levels in the EH&A report (i.e., 1 and 2 ac/MWe)."

The Brady model(9) and all other models based on the mass transfer approach fit the following general mass transfer equation:

$$E = A \cdot f(u) \cdot \Delta e_v$$

where:

- E = total evaporation rate
- A = pond surface area
- $f(u)$ = wind speed function
- Δe_v = water vapor pressure potential for mass transfer between the saturated air at the pond water surface and the ambient air above

The Brady model requires an iterative procedure based on an equilibrium temperature concept for estimating the pond water surface temperature in order to determine Δe_v, given the heat rejection per unit pond surface area (often called pond thermal loading) and local meteorological conditions (dew point, wind speed, and gross solar radiation).

HEDL used the Brady model to determine both the total evaporation rates and natural evaporation rates using estimated pond water surface temperatures and pond equilibrium temperatures respectively. The forced evaporation rates were obtained by subtracting the calculated natural evaporation rates from the total evaporation rates. The natural evaporation rates used in the EH&A's estimates were based on pan evaporation data obtained from weather stations.

Water Consumption Rates of Cooling Systems

Tables 3.2 and 3.3 present a portion of the predicted water consumption rates of cooling towers and cooling ponds compiled in the UE&C study(1). These results are the basis of the observations and conclusions drawn in the study.

As indicated earlier, the predicted cooling system water consumption rates presented in the UE&C study were taken mainly from the EH&A and HEDL studies(2,3,4). The EH&A results are given as single values for each of the 18 water resources regions, whereas the HEDL results are given as low and high values resulting from the consideration of a range of design parameters and operating conditions. All the results were adjusted by UE&C to the same plant heat rejection basis and to the same data units. No other adjustments were made. Therefore, the comparison of the EH&A and HEDL results as presented in the UE&C report(1) reflect the differences in the models for calculating evaporation and the assumptions on blowdown for cooling towers, water consumption credit for cooling ponds due to local runoff and precipitation, etc. as shown in Table 3.1.

The single field study reported in the literature on a closed-cycle cooling pond(10) did not provide measured water consumption rates. The study concluded, however, that the Meyer model predicts pond evaporation rates in excellent agreement with field measurements obtained in the same study.

With respect to the first phase of the concurrent Versar study(5), a complete assessment could not be made by UE&C because of the preliminary nature of the results.

Observations and Conclusions

Based on the separate comparisons of the EH&A results and the HEDL results on cooling towers versus cooling ponds as given in Tables 3.2 and 3.3, UE&C made the following observations with respect to the question of whether the cooling tower or the cooling pond is more water consumptive:

1. The results of the EH&A study as presented in Figures 3.2 and 3.3 clearly show that a cooling tower is more water consumptive than a cooling pond. (Figures 3.2 and 3.3 are the graphic representations of the EH&A results in Tables 3.2 and 3.3.)

2. The results of the HEDL study as given in Figures 3.4 and 3.5 show that in some regions a cooling tower is more water consumptive than a cooling pond, while in other regions a cooling pond is more water consumptive than a cooling tower. (Figures 3.4 and 3.5 are the graphic representations of the HEDL results in Tables 3.2 and 3.3.)

The major conclusions drawn by the first UE&C study with respect to water consumption and evaporation rates of cooling systems are as follows:

1. The two cooling tower evaporation prediction models (Leung-Moore(6) used by EH&A and Winiarski(7) used by HEDL) gave comparable results.

2. The two evaporation rate prediction models for cooling ponds/lakes (Harbeck model*(8) used by EH&A and Brady model (9) used by HEDL) gave disparate results, the rates predicted by the Brady model being consistently higher than those given by the Harbeck model.**

3. Because of the disparity among the predicted cooling ponds/lakes evaporation rates and the unavailability of consistent sets of field data, a definitive conclusion cannot be drawn as to which of the two models, Harbeck or Brady, gives more accurate results.

4. Without the consideration of the actual cooling pond water surface temperature, the use of the Harbeck model for calculating the forced evaporation losses of cooling ponds may result in an underestimation of these losses. The assumption that the pond water surface temperature is equal to the

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* Referred to as the "Harbeck nomograph" in the Versar study(2) and Section 4 of this report.

** These models are also compared in Section 4.

average air temperature is not satisfactory for high thermal loading ponds which correspond to 1.0 acre/MEw or less.*

5. The Brady model appears to result in more credible cooling pond forced evaporation losses than does the Harbeck nomograph because it considers the actual thermal loading of the pond in order to estimate the pond surface temperature.

6. A general conclusion cannot be drawn as to whether a cooling tower or a cooling pond is more water consumptive.

Because of the disparity among the predicted cooling ponds/lakes, evaporation rates and the unavailability of consistent sets of field data, UE&C has recommended that a comprehensive program be carried out to obtain field measurements of pertinent parameters for the purpose of verification and calibration of available pond evaporation models.

COSTS OF COOLING SYSTEM ALTERNATIVES

Cost information on various cooling system alternatives was compiled for all 18 water resources regions in the conterminous United States for both nuclear and fossil power plants. The cooling system alternatives considered included two wet/dry tower systems designed to conserve water, that is, to reduce water consumption below that of comparable wet tower systems. All costs were adjusted to 1978 dollars.

Two main categories of costs were presented in the UE&C report(1): (1) the capital cost for equipment (i.e., cooling device, circulating water system including condenser and electric equipment) and (2) the total evaluated cost. The total evaluated cost includes both the capital cost and the capitalized penalty cost.

While the capital costs can be easily identified, the penalty costs are less definitive and can vary considerably, depending on the economic factors, analysis methods, and penalty items included. Because most cost data sources reviewed lacked much of the design, performance, and cost information needed to calculate these penalty costs, only the capital cost estimates were reported for most of the 18 water resources regions. The total evaluated costs were available for less than half of the water resources regions and were extracted from references where the basic information needed for proper adjustment were available.

Conclusions

1. There is no discernible trend of capital costs either by water resources regions or by the types of cooling systems as illustrated by the cost data in Table 3.4.

* For a plant with a thermal efficiency of 38%, 1.0 acre/MWe is approximately equivalent to 2.5 MWt/acre.

2. With respect to total evaluated costs (sum of capital and capitalized operating costs), the observed cost trend for a specific plant generally remains as expected: a dry cooling system has the highest cost, a once-through cooling system has the lowest cost, and conventional closed-cycle cooling systems, including wet/dry tower systems, lie between the two extremes.

3. The economic impact of using dry tower cooling systems to conserve water may be significantly reduced by the use of wet/dry tower cooling systems. When water is available, however, wet tower cooling systems will continue to be the economic choice under most circumstances.

WATER AVAILABILITY FOR STEAM-ELECTRIC AND OTHER USES

At present, the availability of environmentally acceptable sites for electric power generating plants, whether fossil or nuclear, is strongly influenced by the availability of cooling water. Water can no longer be considered an infinite, undepletable resource. The water availability presented in the UE&C report was based on the then unpublished results of a comprehensive four-year study(12) completed in 1978 by the U.S. Water Resources Council (WRC). The WRC study was accomplished by the cooperative efforts of state, regional, and federal agencies under the direction of the Water Resources Council. In the study, the conterminous United States is divided into 18 water resources regions and further subdivided into 99 subregions. The results of the study included actual water consumption and availability data for 1975 and estimated values for 1985 and 2000.

A portion of the results given in the UE&C study(1) is presented here to illustrate the major points in the conclusions. Tables 3.5 and 3.6 show the water requirements for various uses including public supply, agriculture, industry and mining, and steam-electric generation consumption for 1975 and 1985, respectively. Since the WRC water assessment report was not released in its entirety when the present study was performed, complete information on the assumptions made and methodology used for estimating water consumption rates for various uses was not available.

Tables 3.7 and 3.8 show the annual stream flows in 1975 and 1985, respectively, for the 18 water resource regions and the subregion in each having the most severe water use problem. The dry year assumption used for 1985 (and for the year 2000 in the WRC report) implies that a dry year will occur at least 20 times in each 100 years. Column 1 shows the total stream flow by hydrologic unit. Total consumption due to all uses is shown in Column 2. Total depletion (Column 3) is equal to the sum of the total consumption, exports, and surface evaporation less imports and groundwater mining. The exports and imports represent artificial transfers of freshwater from one region to another. The minimum flow (Column 4) represents the flow desired to maintain habitat for aquatic and riparian plants and animals at subregional outflow points. The available water (Column 5) is the difference between the total stream flow and the minimum flow. Negative values of available water mean that the minimum flow cannot be maintained while satis-

fying the human consumption in full. Tables 3.6 and 3.7 also give the depletion ratios expressed as percentages for the total consumption and for steam-electric generation.

Conclusions

The major conclusions on water availability are as follows:

1. Under dry year conditions, there is insufficient water in most of the 18 water resource regions to satisfy all users at current and projected rates of use. This water shortage situation is particularly critical in the Southwest.

2. Relative to the total water consumption, the percentage consumption for steam-electric generation was 1.23% in 1975 and is estimated to be 2.1% in 1985 and 7.22% in the year 2000.

3. The greatest potential for consumptive water savings lies in the agricultural sector. Since this sector is the largest water consumptive user in most regions, substantial water savings can be obtained with only small percentage reductions in this user category.

LEGAL CONSTRAINTS AND THEIR IMPACT ON CONSUMPTIVE WATER USE

To determine the availability of water from a certain water body for consumptive use by power systems, it is first necessary to examine the laws and regulations that govern water allocation and use. The legal right to use water from a water body is the first determinant as to the water availability for a particular use, even though water may be physically available.

The review study compiled the major features of the institutional framework within which water for energy conversion uses will be sought and developed. The features include the constitutional basis for water laws, important Federal statutes, international treaties, and interstate compacts. Also addressed are the potential impacts of Federal water rights, Indian water rights, and state water laws and policies.

Conclusions

The major conclusions are as follows:

1. There is no simple way to classify all the differing laws and accompanying rules and regulations, since they vary from state to state and depend on court decisions. Constraints on the legal availability of water form a complex web which involves Federal rights, Indian rights, State rights, riparian rights, appropriation rights, beneficial uses, international treaties, and others. Disregard of or any attempt to abrogate these rights (or arrangements) is certain to raise serious objections and entail lengthly litigation.

2. No comprehensive body of law exists, either on the national or state level, on the regulation and consumptive use of water. Present federal and state laws and regulations need codification, and, in some cases, need to be rewritten to enhance understanding and to meet societal needs.

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TABLE 3.1. ASSUMPTIONS USED FOR CALCULATING WATER CONSUMPTION OF COOLING TOWERS AND COOLING PONDS(1)

	ESPEY, HUSTON & ASSOCIATES, INC. (Document No. 7775, September 1977)		HANFORD ENGINEERING DEVELOPMENT LAB (HEDL-TME 76-82, September 1976)	
	Cooling pond	Cooling tower	Cooling pond	Cooling tower
1. Forced Evaporation Model	Harbeck[8] (heat budget method)	Leung & Moore[4]	Brady, Graves & Geyer[9] (mass transfer analysis)	Merkel Equation[5]
2. Storage Volume	No change	N/A	No change	N/A
3. Seepage	Neglected	N/A	Neglected	N/A
4. Precipitation (P)	Included for single purpose pond only but adjusted downward by runoff rainfall ratio	N/A	Included without any correction for runoff	N/A
5. Natural Evaporation (EN)	Included for single purpose pond only; data taken from mean annual lake evaporation	N/A	Included for manmade (single purpose) pond only.	N/A
6. Forced Evaporation (EF)	Included	Included	Included	Included
7. Miscellaneous Plant Use Water	Neglected	Neglected	Neglected	Neglected
8. Ambient Conditions	Major city annual averages for dry bulb and wet bulb temperature and relative humidity in the region	Same as for cooling pond	Mean of monthly average temperatures	Same as for cooling pond
9. Wind Speed	Annual average wind speed adjusted to wind speed at 2 meters above water surface	N/A	Annual average	N/A
10. Blowdown (B)	Neglected	Case 1 = Neglected Case 2 = 25% of evaporation	5% of evaporative requirements	Same as for cooling pond
11. Pond Size	1 acre/MWe and 2 acres/MWe	N/A	1 acre/MWt and 3 acres/MWt	N/A
12. Water Surface Temperature	Same as average dry bulb temperature	N/A	Determined by iteration using the equilibrium temperature concept	N/A
13. Water Consumption (C) Equation Used	C = EN + EF - 1 (1-r) P (for single purpose pond) C = EF (for multipurpose pond)	C = EF + B (blowdown retained) C = EF (blowdown returned)	C = EN + EF - P (for single purpose pond) C = EF (for multipurpose pond)	C = EF + B (blowdown retained) C = EF (blowdown returned)
14. Cycles of Concentration/ Percent Blowdown	N/A	5/25% of evaporation loss	N/A	21/5% of evaporation loss
15. Capacity factor	80% for calculating heat rejected annually by a 1000 MWe fossil fuel plant	Same as for cooling pond	80% for calculating heat rejected annually by a 1000 MWe fossil fuel plant	Same as for cooling pond
16. Effect of Elevation on Water Consumption	Neglected	Considered	Neglected	Considered
17. Cooling Range	Not Specified	Not Specified	Considered for the slug flow pond model only	Not Specified

TABLE 3.2. CONSUMPTIVE WATER USE FOR COOLING TOWERS(1)

Water resource region	Location	Without makeup pond (MGD)						
		Blowdown returned				Blowdown retained		
		EH&A (1974)	EH&A (1977)	HEDL Low	HEDL High	EH&A (1977)	HEDL Low	HEDL High
1. New England	Boston, MA			6.73	7.77		7.07	8.16
	Concord, NH	7.91	8.51	6.77	7.81	10.64	7.10	8.20
	Bangor, ME			6.24	7.58		6.54	7.96
2. Mid-Atlantic	Richmond, VA	8.27	8.87	7.31	8.06	11.09	7.68	8.46
	Philadelphia, PA			7.06	7.94		7.41	8.34
3. South Atlantic-Gulf	Tampa, FL	8.98	9.34	8.08	8.48	11.68	8.49	8.90
	Atlanta, GA			7.85	8.35		8.24	8.77
4. Great Lakes	Detroit, MI	8.03		6.79	7.83		7.13	8.22
	Cleveland, OH			6.90	7.88		7.24	8.28
5. Ohio	Columbus, OH	8.50	8.75	7.01	7.93	10.94	7.36	8.32
	Louisville, KY			7.27	8.06		7.63	8.46
6. Tennessee	Knoxville, TN	8.62		7.40	8.10		7.77	8.50
	Chattanooga, TN			7.49	8.13		7.86	8.54
7. Upper Mississippi	Twin Cities, MN	8.27	8.39	6.44	7.66	10.49	6.76	8.04
	St. Louis, MO		8.87	7.28	8.06	11.09	7.65	8.46
8. Lower Mississippi	Jackson, MS	8.86	9.22	7.81	8.33	11.53	8.20	8.75
	New Orleans, LA			7.92	8.38		8.31	8.80
9. Souris-Red-Rainy	Bismark, ND	7.79	8.51	6.46	7.67	10.64	6.79	8.05
	Duluth, MN			6.26	7.59		6.57	7.97
10. Missouri Basin	N. Platte, NE	8.39	8.87	7.14	8.01	11.09	7.50	8.41
	Great Falls, MT		8.75	6.74	7.78	10.94	7.07	8.17
11. Arkansas-White-Red	Tulsa, OK	8.74		7.57	8.19		7.95	8.60
	Garden City, KS			7.57	8.19		7.95	8.60
12. Texas-Gulf	Dallas, TX	9.09	9.34	7.85	8.33	11.68	8.24	8.75
	Houston, TX			7.91	8.40		8.31	8.82
13. Rio Grande	Albuquerque, NM	8.98	9.34	7.48	8.10	11.68	7.86	8.51
	El Paso, TX			8.02	8.41		8.42	8.83
14. Upper Colorado	Farmington, NM	8.15		7.53	8.16		7.91	8.57
	Gr. Junction, CO			7.11	7.95		7.47	8.35
15. Lower Colorado	Phoenix, AZ	8.98		8.21	8.58		8.62	9.00
	Yuma, AZ			8.33	8.77		8.75	9.21
16. Great Basin	S. Lake City, UT	8.50	8.99	6.88	7.84	11.24	7.22	8.24
	Reno, NV			7.30	8.01		7.67	8.42
17. Pacific Northwest	Seattle, WA	8.27	8.39	6.64	7.81	10.49	6.97	8.20
	Portland, OR			6.77	7.84		7.11	8.23
18. California	Los Angeles, CA	8.75	8.75	7.69	8.21	10.94	8.07	8.62
	Sacramento, CA	9.10	9.10	7.45	8.08	11.38	7.82	8.49

TABLE 3.3. CONSUMPTIVE WATER USE FOR COOLING PONDS AND ONCE-THROUGH COOLING (1)

Water resource region	Location	Multipurpose (natural) pond (MGD) EH&A (77)	Multipurpose (natural) pond (MGD) HEDL Low	Multipurpose (natural) pond (MGD) HEDL High	Single purpose (manmade) pond (MGD) EH&A 1 ac/MWe	Single purpose (manmade) pond (MGD) EH&A 2 ac/MWe	Single purpose (manmade) pond (MGD) HEDL Low	Single purpose (manmade) pond (MGD) HEDL High
1. New England	Boston, MA		5.73	7.21			1.81*	5.91*
	Concord, NH	3.66	5.84	7.34	5.10	4.38	2.84*	6.34*
	Bangor, ME		5.35	6.88			2.39*	5.89*
2. Mid-Atlantic	Richmond, VA	4.49	6.58	8.45	5.73	5.11	5.47*	8.07*
	Philadelphia, PA		6.24	8.00			3.82*	7.19*
3. South Atlantic-Gulf	Tampa, FL	5.53	7.76	9.42	7.57	6.50	10.28	13.28
	Atlanta, GA		7.07	7.83			8.62	9.54
4. Great Lakes	Detroit, MI		5.83	7.46			6.35	7.62
	Cleveland, OH		5.92	7.47			5.22*	7.23*
5. Ohio	Columbia, OH	4.01	6.13	7.93	5.17	4.59	5.72*	7.78*
	Louisville, KY		6.46	8.24			5.73*	8.00*
6. Tennessee	Knoxville, TN		6.61	8.61			4.38*	7.85*
	Chattanooga, TN		6.70	8.62			5.24*	8.12*
7. Upper Mississippi	Twin Cities, MN	4.01	5.42	6.90	5.41	4.71	7.38	9.02
	St. Louis, MO	4.61	6.48	8.19	6.11	5.36	8.04	8.88
8. Lower Mississippi	Jackson, MS	5.08	7.18	8.93	6.56	5.82	7.16*	8.90*
	New Orleans, LA		7.31	9.07			2.30*	7.40*
9. Souris-Red-Rainy	Bismark, ND	4.13	5.25	6.69	6.89	5.51	8.10	11.59
	Duluth, MN		5.13	6.52			5.42	6.62
10. Missouri Basin	N. Platte, NE	4.37	6.05	7.66	8.55	6.46	9.48	13.90
	Great Falls, MT	4.25	5.43	7.00	7.19	5.72	8.59	12.31
11. Arkansas-White-Red	Tulsa, OK		6.82	8.44			8.78	10.50
	Garden City, KS		6.48	7.89			10.71	17.85
12. Texas-Gulf	Dallas, TX	5.55	7.14	8.65	9.89	7.72	10.65	16.16
	Houston, TX		7.42	9.04			9.78	12.51
13. Rio Grande	Albuquerque, NM	4.84	6.26	8.07	12.90	8.87	11.30	18.27
	El Paso, TX		6.94	8.58			13.65	24.92
14. Upper Colorado	Farmington, NM		6.25	8.06			11.44	18.68
	Gr. Junction, CO		6.00	7.82			9.80	14.17
15. Lower Colorado	Phoenix, AZ		7.41	9.37			14.77	26.11
	Yuma, AZ		7.32	9.10			14.90	27.43
16. Great Basin	S. Lake City, UT	4.72	5.55	7.35	7.52	6.12	8.80	11.92
	Reno, NV		6.07	8.12			11.11	17.11
17. Pacific Northwest	Seattle, WA	4.61	5.85	7.79	4.81	4.71	1.20*	6.23*
	Portland, OR		6.07	7.99			-7.55*	3.45*
18. California	Los Angeles, CA	4.01	6.96	8.90	8.91	6.46	11.28	16.47
	Sacramento, CA	4.61	6.69	8.45	10.29	7.45	10.05	13.98

* Average precipitation exceeds natural evaporation

TABLE 3.4. CAPITAL COSTS OF COOLING SYSTEM ALTERNATIVES - FOSSIL PLANTS ($/KW, 1978 DOLLARS)

Water Resource Region	Once Through	Wet Tower	Cooling Pond	40% Wet/Dry*	10% Wet/Dry*	Dry Tower	
						High Back Pressure Turbine	Low Back Pressure Turbine
1. New England	15[3]	22-28[3]	39[3]			34-38[3]	
2. Middle Atlantic		26-27[16]		43[16]	56[16]	45[16]	85[16]
3. S. Atlantic-Gulf	19[20]	24-26[16], 28[3], 22-37[20]	63[20]	53[20]			
4. Great Lakes		25[7], 21-23[8], 44-57[5]	22[8], 44[5]	27[8]		62[7]	
5. Ohio		25[16], 19-25[6]				39-45[5]	
6. Tennessee							
7. Upper Mississippi		19[10]				30[10]	
8. Lower Mississippi							
9. Souris-Red-Rainy							
10. Missouri Basin		23[16]		38-43[16]	47-52[16]	47[16]	101-103[16]
11. Arkansas-White-Red							
12. Texas-Gulf	36[26]		62[26]				
13. Rio Grande							
14. Upper Colorado		21-26[3], 22-24[16]		39-44[16] 52-67[15]	49-57[16]	46-49[16] 73-87[15]	88-108[16]
15. Lower Colorado							
16. Great Basin							
17. Pacific Northwest		25[16], 25-27[35]	69[35]			59[35]	
18. California							

References given in superscripted parentheses are listed in the UE&C Report(1).
* 40% (10%) wet/dry has 40% (10%) of the water consumption of a wet system designed to reject the same quantity of heat.

TABLE 3.5. WATER REQUIREMENTS FOR OFFSTREAM USES (1975)[1]

Region/Worst Subregion	1975					
	Public Supply, MGD (1)	Agriculture, MGD (2)	Industry and Mining, MGD (3)	Steam Electric, MGD (4)	Total Consumption, MGD (5)	Steam Electric÷Total Consumption,% (6)
1. New England	213	51	203	21	488	4.30
0103 Mass-Rhode I Coastal	68	18	53	0	139	0
2. Mid-Atlantic	799	310	676	103	1,888	5.46
0202 Lower Hudson-LI-NNJ	341	53	107	0	501	0
3. South Atlantic-Gulf	1,003	3,690	826	153	5,672	2.70
0305 Southern Florida	232	2,411	102	4	2,749	0.15
4. Great Lakes	595	222	1,627	175	2,619	6.68
0403 SW Lake Michigan	104	19	382	50	555	9.01
5. Ohio	416	199	907	324	1,806	17.94
0503 Muskingum-Scioto-Miami	110	26	108	20	264	7.58
6. Tennessee	71	39	163	42	315	13.33
0602 Lower Tennessee	22	20	40	18	100	18.00
7. Upper Mississippi	347	423	285	129	1,184	10.90
0705 Low/Up Mississippi	97	17	69	36	219	16.44
8. Lower Mississippi	344	3,471	520	54	4,389	1.23
0802 Yazoo-Miss-Quachita	82	655	92	11	840	1.31
9. Souris-Red-Rainy	32	73	16	1	122	0.82
0901 Souris-Red-Rainy	32	73	16	1	122	0.82
10. Missouri Basin	490	16,618	245	68	17,421	0.39
1010 Kansas	35	4,190	25	7	4,257	0.16
11. Arkansas-White-Red	374	8,431	338	89	9,232	0.96
1103 Arkansas-Cimarron	64	2,105	79	13	2,261	0.57
12. Texas Gulf	508	10,730	1,127	99	12,464	0.79
1203 Brazos	85	5,282	93	23	5,483	0.42
13. Rio Grande	191	4,353	108	18	4,670	0.39
1302 Middle Rio Grande	115	1,172	12	8	1,307	0.61
14. Upper Colorado	131	2,454	49	43	2,677	1.61
1401 Green-White-Yampa	72	1,029	27	27	1,155	2.34
15. Lower Colorado	253	4,191	205	63	4,712	1.34
1503 Gila	187	3,182	183	12	3,564	0.34
16. Great Basin	467	3,726	52	8	4,253	0.19
1603 Humboldt-Tonopah Desert	149	1,170	12	0	1,331	0
17. Pacific Northwest	455	13,990	343	16	14,804	0.11
1707 Oregon Closed Basin	96	695	0	0	791	0
18. California	1,796	26,218	440	34	28,488	0.12
1803 San Joaquin-Tulare	236	13,245	88	1	13,570	0.01
Conterminous United States	8,485	99,149	8,130	1,440	117,204	1.23

TABLE 3.6. WATER REQUIREMENTS FOR OFFSTREAM USES (1985)[1]

Region/Worst Subregion	1985					
	Public Supply, MGD (1)	Agriculture, MGD (2)	Industry and Mining, MGD (3)	Steam Electric, MGD (4)	Total Consumption, MGD (5)	Steam Electric÷ Total Consumption,% (6)
1. New England	232	54	347	18	651	2.76
0103 Mass-Rhode I Coastal	74	18	101	0	193	0
2. Mid-Atlantic	894	402	1,017	224	2,537	8.83
0202 Lower Hudson-LI-NNJ	378	69	151	0	598	0
3. South Atlantic-Gulf	1,223	4,275	1,480	722	7,700	9.38
0305 Southern Florida	302	2,673	168	13	3,156	0.41
4. Great Lakes	655	290	1,894	497	3,336	14.90
0403 SW Lake Michigan	111	25	498	133	767	17.34
5. Ohio	464	194	1,223	656	2,537	25.86
0503 Muskingum-Scioto-Miami	125	28	173	41	367	11.17
6. Tennessee	83	48	287	231	649	35.59
0602 Lower Tennessee	26	25	81	123	255	48.24
7. Upper Mississippi	372	573	366	352	1,663	21.17
0705 Low/Up Mississippi	102	23	104	29	258	11.24
8. Lower Mississippi	373	3,667	804	118	4,962	2.38
0802 Yazoo-Miss-Quachita	88	744	160	35	1,027	3.41
9. Souris-Red-Rainy	33	180	21	0	234	0
0901 Souris-Red-Rainy	33	180	21	0	234	0
10. Missouri Basin	550	20,670	259	243	21,722	1.12
1010 Kansas	37	4,357	33	26	4,453	0.58
11. Arkansas-White-Red	410	8,903	417	237	9,967	2.38
1103 Arkansas-Cimarron	66	2,637	83	12	2,798	0.43
12. Texas Gulf	572	8,761	1,591	270	11,194	2.41
1203 Brazos	88	4,013	105	107	4,313	2.48
13. Rio Grande	209	4,413	144	9	4,775	0.19
1302 Middle Rio Grande	127	1,239	28	7	1,401	0.50
14. Upper Colorado	151	2,966	73	120	3,310	3.63
1401 Green-White-Yampa	81	1,135	36	62	1,314	4.72
15. Lower Colorado	335	4,130	271	134	4,870	2.75
1503 Gila	250	3,114	242	37	3,643	1.02
16. Great Basin	521	3,588	86	44	4,239	1.04
1603 Humboldt-Tonopah Desert	166	1,304	21	16	1,507	1.06
17. Pacific Northwest	538	16,941	520	134	18,133	0.74
1707 Oregon Closed Basin	99	980	0	0	1,079	0
18. California	1,979	27,226	595	101	29,901	0.34
1803 San Joaquin-Tulare	253	14,020	114	26	14,413	0.18
Conterminous United States	9,594	107,281	11,395	4,110	132,380	3.10

TABLE 3.7. STREAM FLOW DEPLETION (1975)[1]

Region/Worst Subregion	1975						
						Depletion Ratios	
	Total Stream Flow, MGD (1)	Total Consumption, MGD (2)	Total Depletion, MGD (3)	Minimum Flow, MGD (4)	Available Water, MGD (5)	Total Stream Flow, % (6)	Steam Electric, % (7)
1. New England	63,215	488	485	69,001	-5,786	0.77	0.03
0103 Mass-Rhode I Coastal	3,770	139	-40	4,003	-233	-1.06	0
2. Mid-Atlantic	62,573	1,888	1,375	68,840	-6,267	2.20	0.16
0202 Lower Hudson-LI-NNJ	10,436	501	-957	13,870	-3,434	-9.17	0
3. South Atlantic-Gulf	169,139	5,672	5,338	188,655	-19,516	3.16	0.09
0305 Southern Florida	6,740	2,749	2,674	6,590	150	39.67	0.06
4. Great Lakes	59,823	2,619	2,570	63,951	-4,128	4.30	0.29
0403 SW Lake Michigan	1,395	555	555	875	520	39.78	3.58
5. Ohio	142,805	1,806	1,805	160,520	-17,715	1.26	0.23
0503 Muskingum-Scioto-Miami	9,704	264	264	9,613	91	2.72	0.21
6. Tennessee	36,215	315	315	38,480	-2,265	0.87	0.12
0602 Lower Tennessee	35,999	100	99	38,480	-2,481	0.28	0.05
7. Upper Mississippi	88,405	1,184	-838	110,750	-22,345	-0.95	0.15
0705 Low/Up Mississippi	89,461	219	218	110,750	-21,289	0.24	0.04
8. Lower Mississippi	277,549	4,389	3,975	359,033	-81,484	1.43	0.02
0802 Yazoo-Miss-Quachita	246,457	840	733	319,540	-73,083	0.30	0.00
9. Souris-Red-Rainy	3,498	122	138	3,673	-175	3.95	0.03
0901 Souris-Red-Rainy	3,498	122	138	3,673	-175	3.95	0.03
10. Missouri Basin	46,716	17,421	19,373	33,958	12,758	41.47	0.15
1010 Kansas	3,800	4,257	3,500	3,706	94	92.11	0.18
11. Arkansas-White-Red	38,203	9,232	6,260	46,169	-7,966	16.3°	0.23
1103 Arkansas-Cimarron	451	2,261	710	2,867	-2,416	157.43	2.88
12. Texas-Gulf	15,249	12,464	8,561	22,917	-7,668	56.14	0.65
1203 Brazos	632	5,483	2,779	3,360	-2,728	439.72	3.64
13. Rio Grande	4,120	4,670	4,507	2,287	1,833	109.39	0.44
1302 Middle Rio Grande	1,012	1,307	1,090	888	124	107.71	0.79
14. Upper Colorado	11,215	2,677	4,195	7,947	3,268	37.41	0.38
1401 Green-White-Yampa	4,344	1,155	1,664	3,056	1,288	38.31	0.62
15. Lower Colorado	6,910	4,712	7,965	6,864	46	115.27	0.91
1503 Gila	-536	3,564	1,583	676	-1,212	-295.34	-2.24
16. Great Basin	9,984	4,253	3,886	8,177	1,807	38.92	0.08
1603 Humboldt-Tonopah Desert	2,002	1,331	1,138	2,137	-135	56.84	0
17. Pacific Northwest	228,846	14,804	16,140	214,004	14,842	7.05	0.01
1707 Oregon Close Basin	1,221	791	802	1,082	139	65.68	0
18. California	50,750	28,488	22,518	33,130	17,620	44.37	0.07
1803 San Joaquin-Tulare	9,775	13,370	9,825	2,841	-903	100.51	0.01
Conterminous United States	1,315,215	117,204	108,568	---	---	8.25	0.11

TABLE 3.8. STREAM FLOW DEPLETION (1985) (DRY YEAR ASSUMPTION)[1]

Region/Worst Subregion	1985						
						Depletion Ratios	
	Total Stream Flow, MGD (1)	Total Consumption, MGD (2)	Total Depletion, MGD (3)	Minimum Flow, MGD (4)	Available Water, MGD (5)	Total Stream Flow, % (6)	Steam Electric, % (7)
1. New England	63,215	651	652	69,001	-5,786	1.03	0.03
0103 Mass-Rhode I Coastal	3,769	193	-59	4,003	-234	-1.57	0
2. Mid-Atlantic	62,604	2,537	2,057	68,840	-6,236	3.29	0.36
0202 Lower Hudson-LI-NNJ	10,414	598	-853	13,870	-3,456	-8.19	0
3. South Atlantic-Gulf	169,476	7,700	7,706	188,655	-19,179	4.55	0.43
0305 Southern Florida	6,814	3,156	3,156	6,590	224	46.32	0.19
4. Great Lakes	59,850	3,336	3,314	63,951	-4,101	5.54	0.83
0403 SW Lake Michigan	1,394	767	765	875	519	54.88	9.54
5. Ohio	142,475	2,537	2,539	160,520	-18,045	1.78	0.46
0503 Muskingum-Scioto-Miami	9,703	367	367	9,613	90	3.78	0.42
6. Tennessee	36,215	649	646	38,480	-2,265	1.78	0.64
0602 Lower Tennessee	35,822	255	253	38,480	-2,658	0.71	0.34
7. Upper Mississippi	83,715	1,663	-368	110,750	-27,035	-0.44	0.42
0705 Low/Up Mississippi	84,340	258	257	110,750	-26,410	0.30	0.03
8. Lower Mississippi	270,760	4,962	4,963	359,033	-88,273	1.83	0.04
0802 Yazoo-Miss-Quachita	239,071	1,027	1,028	319,540	-80,469	0.43	0.01
9. Souris-Red-Rainy	3,498	234	193	3,673	-175	5.52	0
0901 Souris-Red-Rainy	3,498	234	193	3,673	-175	5.52	0
10. Missouri Basin	49,275	21,722	26,612	33,958	15,317	54.01	0.49
1010 Kansas	5,400	4,453	5,372	3,706	1,694	99.48	0.48
11. Arkansas-White-Red	43,660	9,967	12,696	46,169	-2,509	29.08	0.54
1103 Arkansas-Cimarron	2,649	2,798	3,457	2,867	-218	130.50	0.45
12. Texas-Gulf	20,827	11,194	13,038	22,917	-2,090	62.60	1.30
1203 Brazos	4,399	4,313	5,465	3,360	-1,039	124.23	2.43
13. Rio Grande	4,779	4,775	5,337	2,287	2,492	111.68	0.19
1302 Middle Rio Grande	1,072	1,401	1,444	888	184	134.70	0.65
14. Upper Colorado	11,214	3,310	5,015	7,947	3,267	44.72	1.07
1401 Green-White-Yampa	4,344	1,314	1,982	3,056	1,288	45.63	1.43
15. Lower Colorado	8,504	4,870	10,177	6,864	1,640	119.67	1.58
1503 Gila	1,583	3,643	3,790	676	907	239.42	2.34
16. Great Basin	10,576	4,239	4,392	8,177	2,399	41.53	0.42
1603 Humboldt-Tonopah Desert	2,288	1,507	1,600	2,137	151	69.93	0.70
17. Pacific Northwest	229,475	18,133	20,147	214,004	15,471	8.78	0.06
1707 Oregon Close Basin	1,235	1,079	1,113	1,082	153	90.12	0
18. California	52,947	29,901	26,511	33,130	19,817	50.07	0.19
1803 San Joaquin-Tulare	11,025	14,413	11,195	2,841	8,184	101.54	0.24
Conterminous United States	1,323,065	132,380	145,627	---	---	11.01	0.31

Figure 3.1. Map Showing Water Resource Regions Defined by Water Resources Council (1)

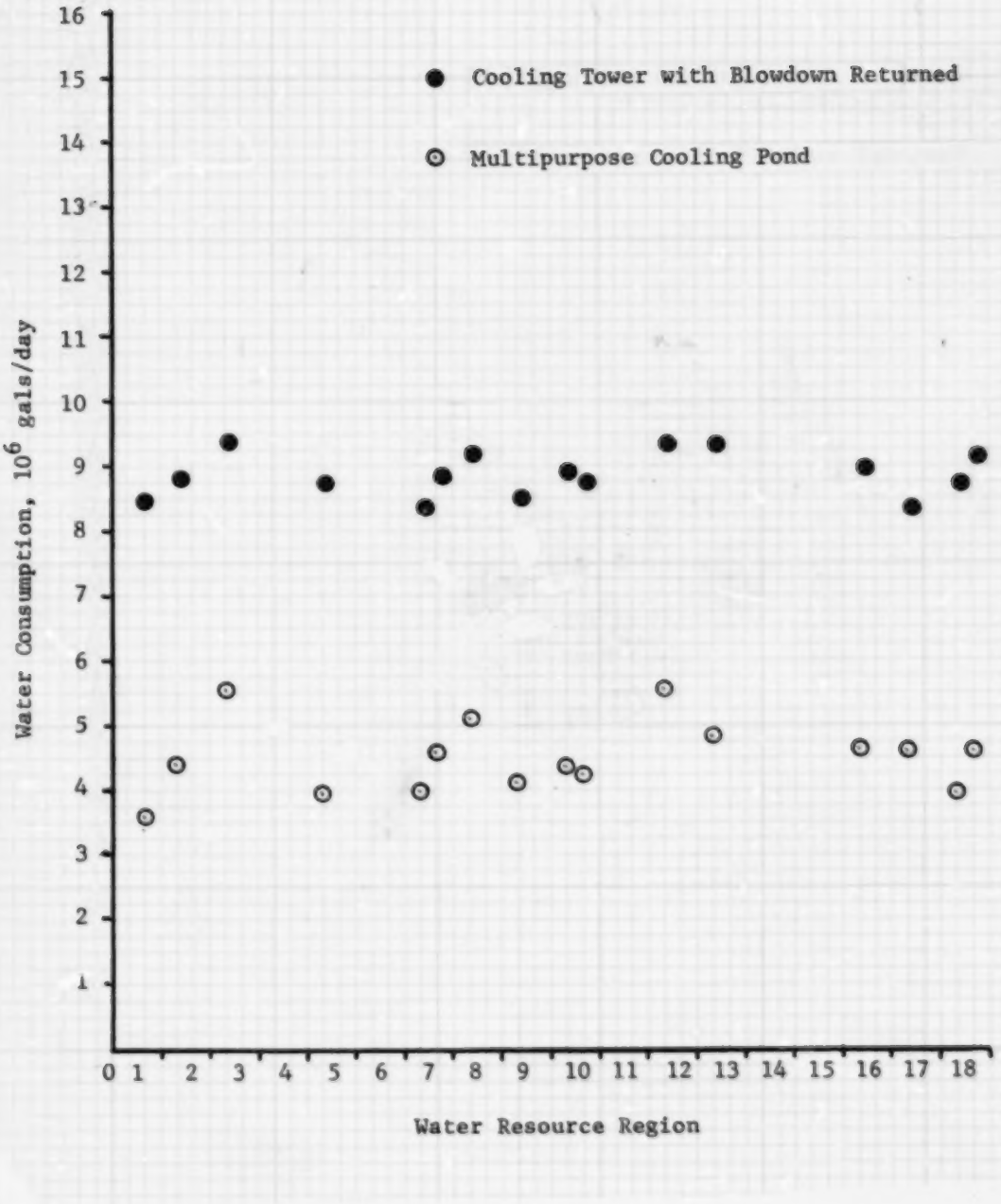

Figure 3.2. Comparison of water consumption rates obtained by EH&A study(2) for multipurpose cooling ponds and cooling towers with blowdown returned

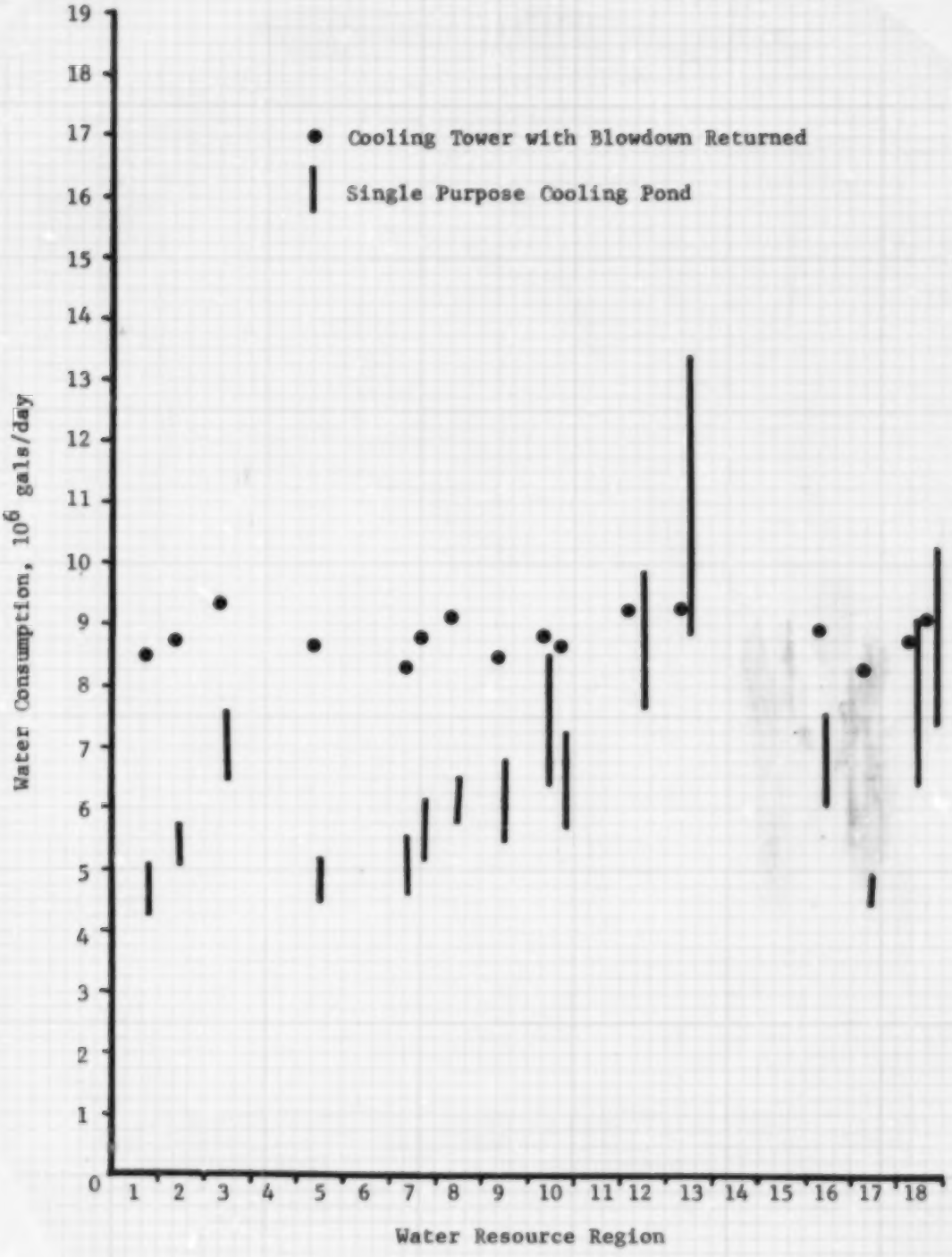

Figure 3.3. Comparison of water consumption rates obtained by EH&A study(2) for single purpose cooling ponds and cooling towers with blowdown returned

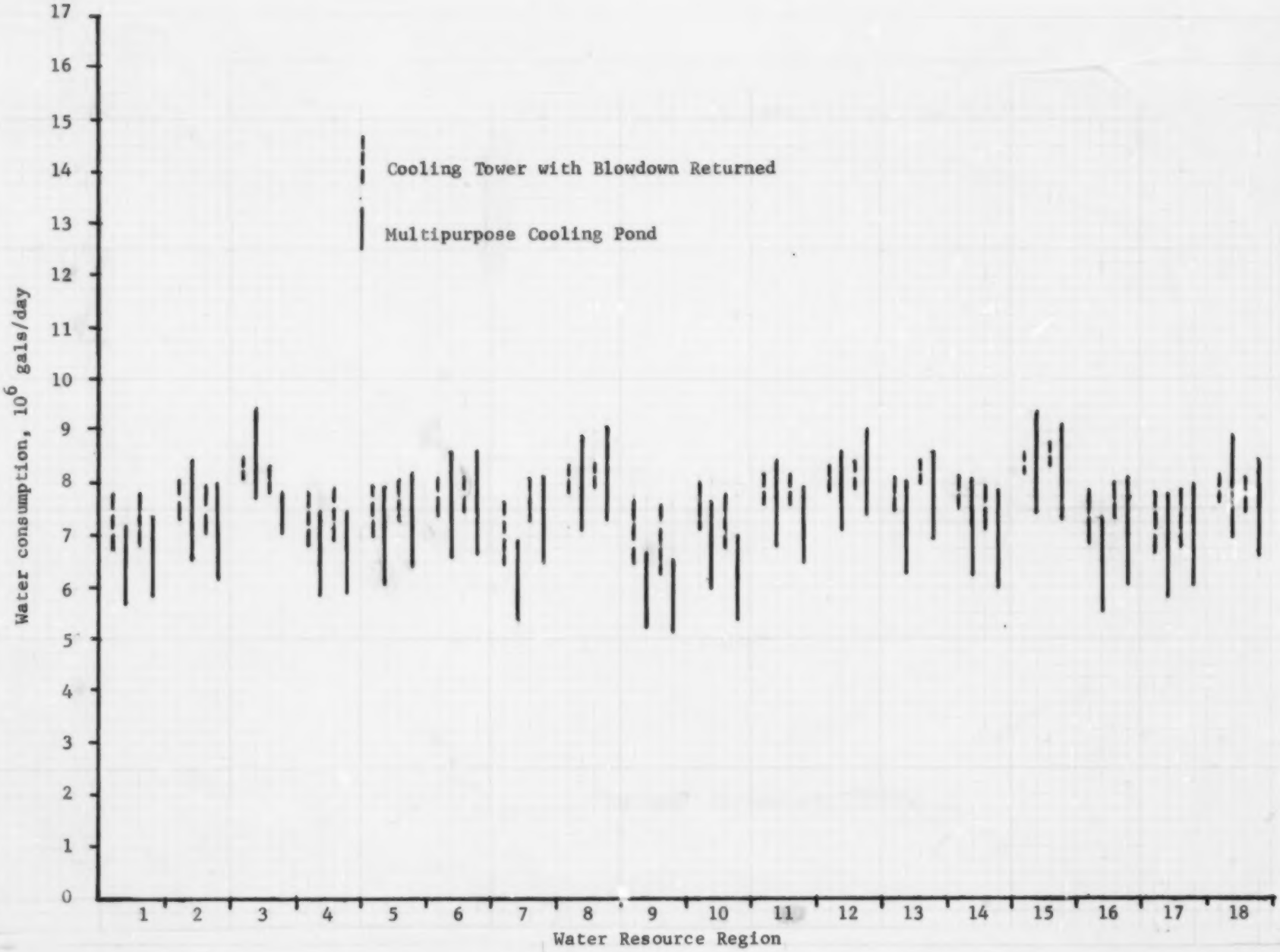

Figure 3.4. Comparison of water consumption rates obtained by HEDL study(1) for multipurpose cooling ponds and cooling towers with blowdown returned

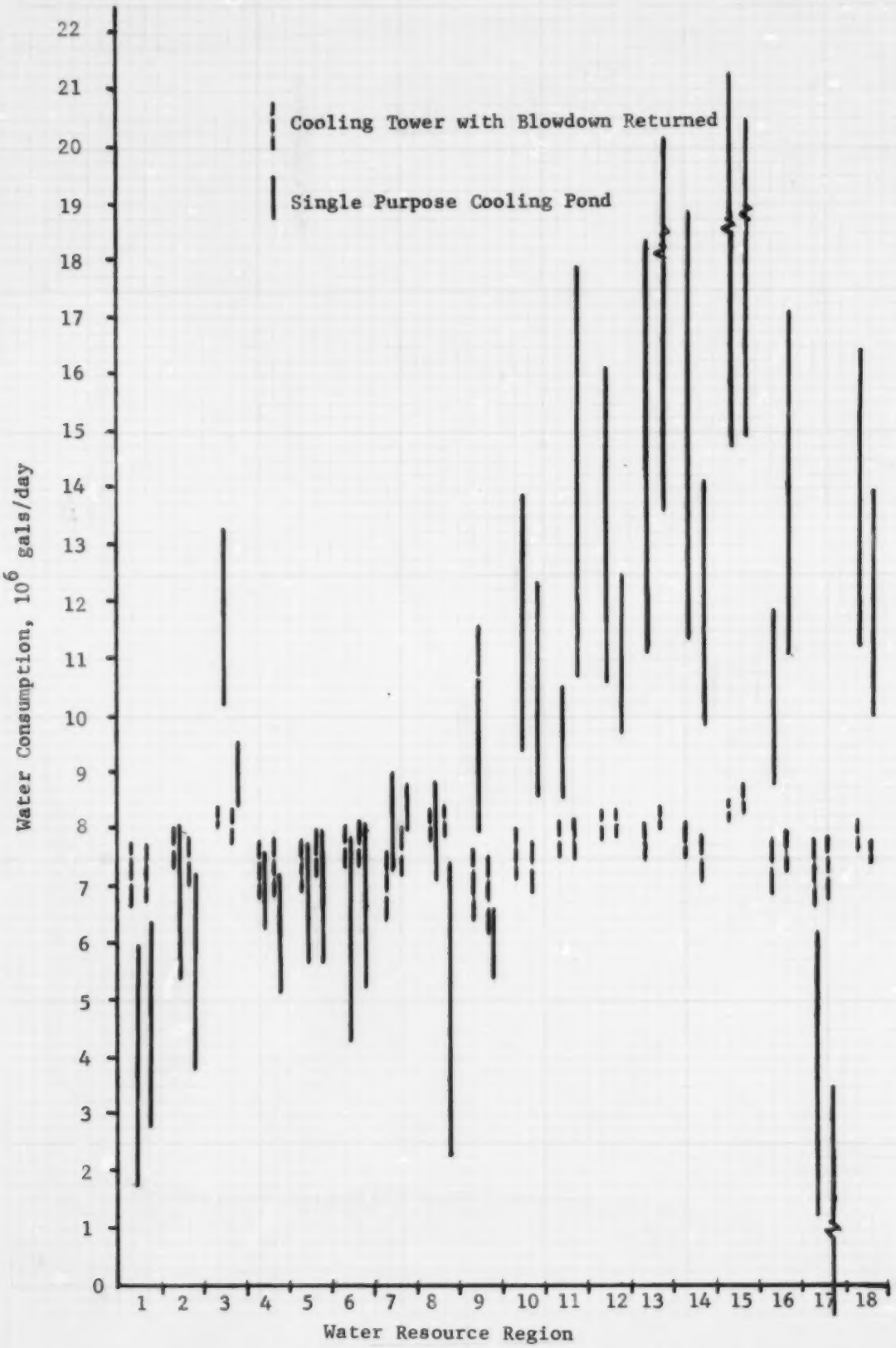

Figure 3.5. Comparison of water consumption rates obtained by HEDL study (4) for single purpose cooling ponds and cooling towers with blowdown returned

SECTION 4

SUMMARY OF VERSAR REPORT: COMPARISON OF MODEL PREDICTIONS AND CONSUMPTIVE WATER USE OF CLOSED CYCLE COOLING SYSTEMS

The primary objectives of this study conducted by Versar, Inc. were: 1) to survey and identify simple generic models for predicting evaporation rates from power plant closed-cycle cooling systems using wet towers and ponds/lakes, 2) to verify and calibrate these generic evaporation models with field data from operating power plants, and 3) to determine which of the two types of cooling systems is more water consumptive in terms of evaporation.

To achieve these objectives the available technical literature was reviewed and available field data were solicited and acquired for a number of operating power plants. Evaporation prediction models satisfying certain criteria were selected and evaluated using available field data provided by utilities and data estimated by Versar when the field data were insufficient for the intended analyses. Comparisons of the tower and pond evaporation rates on a regional basis were then made to determine whether the tower or the pond is more water consumptive.

SELECTION OF EVAPORATION MODELS FOR EVALUATIONS

Several evaporation prediction models were selected by Versar for model verification with field measurements. The models, one for cooling towers and five for cooling ponds/lakes, were selected on the basis that they are simple, non-iterative, and generic (i.e., not intended for site or plant specific applications).

For cooling towers, the model selected was the mechanical draft cooling tower model developed by Paul Leung and Raymond Moore from studies performed for the Navajo Station in northern Arizona(2). The model, called the Leung-Moore model, is represented by a set of four nomographs.

For cooling ponds/lakes, five evaporation prediction models were selected. The models are identified in the Versar report by the names of the investigators, with or without the names of the lakes/ponds where tests were made: (a) Marciano-Harbeck (Lake Hefner); (b) Harbeck-Koberg-Hughes (Lake Colorado City); (c) Meyer; (d) Brady et al.; and (e) Harbeck nomograph.

The first four models are based on mass transfer concepts and fit a general mass transfer equation of the following form:

$$E = f(w)\ \Delta e_u A$$

where:

E = total evaporation rate
f(w) = wind function
Δe_u = water vapor pressure potential for mass transfer between saturated air at pond surface and ambient air above
A = pond surface area

Each of these four models has a different empirically developed wind function. These models have been evaluated and compared in a Littleton Research and Engineering Corporation study(3).

The Brady model for cooling pond was also used in the Hanford Engineering Laboratory study(4), while the Leung-Moore model for cooling tower and the Harbeck nomograph for cooling ponds were used in the Espey, Huston & Associates (EH&A) studies(5,6). The HEDL and EH&A studies were reviewed and evaluated in the first UE&C study(7) which was summarized earlier in this report.

ACQUISITION OF FIELD DATA AND VERIFICATION OF EVAPORATION PREDICTION MODELS

To verify the evaporation prediction models using available field data of cooling towers and cooling ponds, Versar contacted utilities across the country. Twenty-one utilities responded to the data requests; twelve of them provided data in time for the study. The data supplied by the utilities include fifteen wet cooling tower systems, seven cooling ponds, and one cooling canal system. These data are summarized in Tables 4.1 and 4.2 for cooling towers and cooling ponds/lakes, respectively.

The data provided by the utilities and presented in Tables 4.1 and 4.2, however, are not entirely field data. They include some design data provided by the utilities and also some data estimated by Versar. Since in most cases the data provided were incomplete for the intended evaluations, Versar made approximations or estimations to make up for the missing data. However, the estimations were done on a consistent basis with the best available information. The aforementioned data were used as inputs for both the models and the water budget equations to determine evaporation rates.

When using the material balance method, the evaporation rate was determined from the difference between the inflow to the system and the outflow from the system. The inflow for towers is the makeup water; the inflow for ponds/lakes may include the stream flow into the lake (makeup), the local runoff, and the direct precipitation. The outflow for towers may include blowdown and drift, and that for ponds/lakes may include blowdown (outflow) and seepage. The tower drift and pond seepage are usually small compared to the other terms, and consequently, they were neglected in Versar's evaluation as well as those reported in Section 3. The local runoff was determined from direct precipitation by multiplying it with an estimated runoff coefficient based on local USGS information.

The comparisons of the evaporation results obtained in the Versar study for cooling towers and cooling ponds are shown in Tables 4.3 and 4.4, respectively. The comparisons include both the values for the specific plants and the normalized values.

Table 4.3 illustrates the accuracy of the Leung-Moore model relative to material balance values. On the average, the Leung-Moore model predicted evaporation rates to within ± 15 percent of the material balance results when the power plants with capacity factors over 50 percent were considered. Cooling tower evaporation rates for peaking and cycling units (capacity factor below 50 percent) are not well simulated by the model.

Table 4.4 illustrates the accuracy of the five cooling pond/lake models compared with material balance values. The power plants associated with the cooling ponds/lakes were mostly large base load units. The comparison shows that the Harbeck-Koberg-Hughes and Meyer models give better predictions than the other three models.

REGIONAL COMPARISON OF COOLING SYSTEM EVAPORATION RATES

One of the stated primary objectives of the study was to compare water consumption rates of cooling towers and cooling ponds/lakes on a regional basis. In actual analysis, Versar compared the evaporation rates of the two types of cooling systems and considered that this also represented the comparison of water consumption rates of these cooling systems.*

Twenty cooling systems for sixteen plants investigated in the Versar study provided comparisons for seven water resources regions. The comparison is shown in Table 4.5. The predicted evaporation rates for towers are the values calculated by the Leung-Moore model, and those for the cooling ponds are the values calculated by the model which gives the closest prediction to the material balance value. The results in Table 4.5 show that cooling ponds in these cases evaporate more water than cooling towers. The relationship is most dominant in the southern regions (Lower Colorado, Rio Grande, Texas Gulf) where high natural evaporation rates exist.

CONCLUSIONS

The major conclusions drawn from the Versar study concerning water evaporation and consumption of cooling towers and cooling ponds/lakes are summarized as follows:

1. For cooling towers at base load plants (blowdown returned and no makeup impoundments), the predicted evaporation rates by the Leung-Moore model(2) are in good agreement with those determined from material balances (within ± 15%).

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* In the UE&C study, the water consumption of a power plant cooling system is defined as that portion of the water removed from and not returned to the surface water resources of a given area. In the Versar study, the water consumption is implicitly defined as evaporation only. Both definitions have been used in previous water consumption studies.

2. For cooling ponds/lakes, the Harbeck-Koberg-Hughes model(3) (Lake Colorado City) and Meyer model(3) generally give predictions within ± 15% of the material balance results; the Brady model(3), Harbeck model(8), and Marciano-Harbeck model(3) (Lake Hefner) give consistently lower evaporation rates than the material balances values. Generally, the Brady model predictions approximated the material balance values more closely than the Harbeck and Lake Hefner models.

3. Cooling ponds/lakes generally evaporate more water than cooling towers.

4. The satisfactory comparison of the cooling tower evaporation rates predicted with the Leung-Moore model with material balance values developed using field data supplemented with estimations where needed to complete the evaluation suggest that this model can adequately be used for estimating cooling tower evaporation rates.

5. Comparisons of the evaporation rates predicted with the five cooling pond/lake models and the results determined from material balances developed using field data supplemented with estimations where needed to complete the evaluation indicate that predictions from the Harbeck-Koberg-Hughes model and the Meyer model are preferable over the other models for estimating cooling pond/lake evaporation rates.

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TABLE 4.1 COOLING TOWER DATA (1)

Station Name	Huntington	NAVJO	North Main - Unit 1						Permian
Unit No.	Unit 1		Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	
Utility Name	Utah Power & Light	Arizona Public Service	Texas Electric Service Company						Texas Electric
Test Period	1976 Annual Average	Test 1-A (1 hr.) August 6, 1977 / Test 2-A (2 hrs.) August 20, 1977	1 Week Performance Test January 21-26, 1960						6 hours November 5, 1958
Plant Capacity, MWe	400	750	750	85.85	85.85	85.85	85.85	85.85	85.85	100
Capacity Factor, %	80	107	100	48	63	35	76	82.5	100	Not Known
Unit Heat Rejection, Btu/kWh	5100	4480	4480	6018	5979	6315	5948	6063	6119	4788
Circulating Water Flow, GPM	185,800	145,326	147,306	66,244	63,116	64,092	63,429	64,189	63,765	69,550
Makeup Water Flow, GPM	4,000	3,482	3,432	508	535	553	509	644	710	704
Blowdown Rate, GPM	320	0	0	201	250	250	141	141	148	0
Range, ^{o}F	23.9	28.1	27.7	7.8	10.0	6.0	12.0	14.0	16.4	13.8
Approach, ^{o}F	17.5	20.3	22.7	15.9	21.9	13.7	22.2	22.1	23.3	17.2
Air Flow Rate, SCFM	18×10^6	2.8×10^7	2.9×10^7	3.5×10^6	3.5×10^6	3.5×10^6	3.5×10^6	3.5×10^6	3.5×10^6	3.3×10^6
Outlet Air Temperature, ^{o}F	82–97	94.8	92.0	66	71.5	64	78	84	91.5	92
Approximate Drift Loss, GPM	372	293	295							12

TABLE 4.1. COOLING TOWER DATA (1) (cont'd)

Station Name	Newman/Rio Grande Stations						Moses	Couch	Lynch
Unit No.	Unit 1	Unit 2	Unit 3	Unit 6	Unit 7	Unit 8	Units 1 and 2	Units 1 and 2	Units 1, 2 and 3
Utility Name	El Paso Electric Company						Arkansas Power and Light	Arkansas Power and Light	Arkansas Power and Light
Location (Water Resource Region)									
Test Period	August, 1977			July, 1977			1976 Annual Data	1976 Annual Data	1976 Annual Data
Plant Capacity, MWe	86	90	110	50	50	165	126	161	239
Capacity Factor, %	59.3	85.5	98.2	30.5	58.5	48	11	29	12
Unit Heat Rejection, Btu/kWh	5680	5715	5310	6545	5615	5150	7600(1) 7575(2)	7370(1) 6650(2)	9500(1) 8090(2) 7950(3)
Circulating Water Flow, GPM	43,000	42,000	42,500	36,800	28,350	56,300	79,650	116,500	164,500
Makeup Water Flow, GPM	1580	1484	1672	500	608	1627	1030	622	1186
Blowdown Rate, GPM	375	350	397	145	175	407	221	160	0.1
Range, ^{o}F	25	25	28	10	15	22	8.4	12	9.8
Approach, ^{o}F	24	20	18	12	16	17	14	14	14
Air Flow Rate, SCFM	2.3×10^6	3×10^6	4.1×10^6	3.5×10^6	3.0×10^6	8.7×10^6	8.9×10^6	11.3×10^6	12.5×10^6
Outlet Air Temperature, ^{o}F	104	97	97	86	91	94	66	83	68
Approximate Drift Loss, GPM	87	84	85	74	57	113	160	46.6	66

TABLE 4.1. COOLING TOWER DATA (1) (cont'd)

Station Name Unit No.	Homer City Plant			Clay Boswell Plant Unit 3			Koshkonong Plant * Unit 1
Utility Name	Pennsylvania Electric Company (Natural Draft Tower)			Minnesota Power & Light Company			Wisconsin Electric Power Company
Location (Water Resource Region)							
Test Period	1977 Average January	April	July	1977 Average January	August	Annual	
Plant Capacity, MWe	1328	1328	1328	350	350		900
Capacity Factor, %	49.41	34.94	57.35	86	93		100
Unit Heat Rejection, Btu/kWh	5238	5576	5685	5130	4965		7383
Circulating Water Flow, GPM	205,500	205,500	205,500	130,800	130,781		524,100
Makeup Water Flow, GPM	9186	8889	14,150	--	--	2616	12,500
Blowdown Rate, GPM	2595	2660	2838	--	--	500	1850
Range, ^{o}F	34.9	28.1	28.3	20	15.6		26
Approach, ^{o}F	48	24	18	32.9	21.8		18
Air Flow Rate, SCFM	12.38×10^6	8.25×10^6	14.44×10^6	12×10^6	12×10^6		40.2×10^6
Outlet Air Temperature, ^{o}F	93	92	105	64.3	89.5		82
Approximate Drift Loss, GPM	20.6	20.6	20.6	13	13		26

* All of the data given are design values.

TABLE 4.2 COOLING POND/LAKE DATA (1)

Station Name / Unit No.	Cholla	Morgan Creek	Kincaid	Powerton No. 5	Powerton No. 6	H. B. Robinson	Belews Creek	Mt. Storm	
Utility Name	Arizona Public Service Company	Texas Electric Service	Commonwealth Edison Company	Commonwealth Edison Company		Carolina Power and Light Company	Duke Power Company	Virginia Electric and Power Company	
Test Period	1974-1976 Annual Average	1959-1960	1977 Annual Average	1973 Annual	1977 Annual	1975-1976 Average	1977 Annual Average	January 1977	July 1977
Plant Capacity, MWe	120	102	1319	840	945	885	2286	1662	1662
Capacity Factor, %	70	---	34	51.7	47.1	67	66	69 (No. 1), 61 (No. 2), 35.4 (No.3)	
Unit Heat Rejection, Btu/kWh	4820		5200	4540	4540	4900	4225	4280	4280
Circulating Water Flow, GPM	27,800	493,714	479,981	690,562	690,562	500,923	1,050,332	889,020	889,020
Flow Rate into Pond, GPM	1696	6,075	28,800	19,666	19,666	131,202	26,222	182,743	142,378
Flow Rate Out of Pond, GPM	313	860	19,300	14,772	14,772	125,232	11,381	7,676	3,124
Cooling Range, ^{o}F	Not Given		13.8	18.8	19.3	14.1	18.40	33.3	33.3
Condenser Makeup Water Temperature, ^{o}F	56.9	68	62.0	61.5	60.6	71.6	67.9	42.2	83.1
Effective Pond Surface Area for Cooling Acres	340	1100	2400	1426	1426	2250	3553	1130	1130
Water Volume of Pond, Acre-feet	Not Given	31,000	33,500	15,600	15,600	41,000	176,000	49,000	49,000
Drainage Area, sq. mi.	Not Given	326	76.6	---	---	173	70.9	30	30

TABLE 4.3. COMPARISON OF ALL COOLING TOWER EVAPORATION RATES, AS CALCULATED AND NORMALIZED[1]

Plant/Unit Size (MW)	Time Period	Material Balance (cu m/min)	Model Prediction (cu m/min)	Ratio Model/ Material Balance	Normalized Evaporation cu m/min-MW		Normalized Evaporation cu m/10^6 kcal	
					Material Balance	Model	Material Balance	Model
Huntington/400	annual	12.5[b]	12.8	1.02	0.039	0.040	1.84[b]	1.88
Navajo/750	hourly-summer	12.6 (12.2)[c]	13.8	1.10	0.016	0.018	0.85 0.88[c]	0.96
N. Main/85	hourly-summer	1.46	1.96	1.34	0.025	0.034	0.99	1.32
Permian/100	hourly-summer	3.0	3.1	1.03	0.030	0.031	1.49	1.54
Newman-1/86	August	4.2	3.7	0.88	0.082	0.072	3.44	3.02
-2/90	August	4.0	3.9	0.98	0.052	0.051	2.17	2.15
-3/110	August	4.5	4.5	1.00	0.042	0.042	1.86	1.86
Rio Grande-6/50[a]	July	1.1	2.4	2.18	0.072	0.157	2.62	5.73
-7/50	July	1.4	2.1	1.50	0.050	0.075	2.11	3.17
-8/165[a]	July	4.2	6.5	1.55	0.053	0.082	2.45	3.79
Moses/126[a]	annual	2.45	7.2 (0.85)[e]	3.0 (0.35)[e]	0.177	0.531 (0.061)[e]	5.54	16.5 (1.92)[e]
Lynch/239[a]	annual	4.16	14.4 (1.7)[e]	3.5 (0.41)[e]	0.145	0.508 (0.047)[e]	4.93	17.3 (1.60)[e]
Couch/161[a]	annual	1.62	7.6 (2.2)[e]	4.7 (1.35)[e]	0.035	0.163 (0.059)[e]	1.02	4.77 (1.73)[e]
Homer City/1328	January	16.9	14.7	0.87	0.030	0.026	1.19	1.04
	July	40.5	26.0	0.67	0.054	0.036	2.62	1.68
		(18.6)[d]		(1.44)[d]	(0.026)[d]		(1.20)[d]	
Clay Boswell/350	January		5.61			0.019		0.86
	August		8.41			0.026		1.24
	annual	7.95		0.88	0.031		1.50	
Koshkonong Nuclear/900	annual	40	42	1.05	0.044	0.046	1.43	1.50
				range	1.50-0.67 (baseload plants)			

a Units with capacity factors less than 50 percent
b Based on constant outlet air temperature
c Marley test results
d Gilbert Assoc. curves
e Results X capacity factor

TABLE 4.4. SUMMARY OF COOLING POND/LAKE MATERIAL BALANCE AND COMPUTER MODEL EVAPORATION VALUES ON 'AS IS' AND NORMALIZED BASES[1]

Plant/Unit or Station Size (MW)	Time Period	Material Balance (cu m/min)	Model Predicted (cu m/min)					Evaporation Rate Ratio Model/Material Balance					Area/Power (acres/MW)	Normalized Evaporation Rate for Model Giving Closest Prediction to the Material Balance Value		
			QH	QC	QM	QB	HN	QH	QC	QM	QB	HN	ha/MW	(cu m/min-MW)	(cu m/min-ha)	cu m/10^6 kcal
Cholla/120	July	—	6.8	9.9	8.7	7.6							(2.83)	0.103	0.073	5.81
	annual	6.9	4.3	6.3	6.0	5.3	5.0	0.62	0.91	0.87	0.77	0.72	1.15	0.075	0.046	3.70
Morgan Creek/102 (equivalent)	August	29.8	22.6	33.3	30.0	25.6		0.76	1.12	.01	0.86		(4)	0.294	0.067	11.1
	annual	21.0	12.2	17.9	15.0	13.9	14.7	0.58	0.85	0.71	0.66	0.70	1.62	0.201	0.043	7.60
H.B. Robinson/885	August	76.5	38.1	56.0	62.9			0.50	0.73	0.82			(2.54)	0.089	0.069	4.37
	annual	44.6	26.0	38.3	40.2	34.0	26.8	0.58	0.86	0.90	0.76	0.65	1.03	0.068	0.046	3.31
Belews Creek/ 2,286	August	99.1	68.5	101	109	83.5		0.69	1.02	1.09	0.86		(1.64)	0.062	0.070	3.45
	annual	90.9	37.8	55.5	58.7	46.5	48.8	0.42	0.61	0.65	0.51	0.54	0.66	0.039 (0.060)[a]	(0.041) (0.063)[a]	2.19
Mt. Storm/1,662	January		7.7	11.2	10.6	10.0							(0.68)	(0.012-0.026)	(0.019-0.024)	0.45-0.68
	July		10.9	16.2	24.3	19.2							0.275		(0.024-0.053)	0.66-1.5
Kincaid/1,319	August		44.7	65.8	63.1	51.5							(1.64)			
	annual	36.2	26.4	39.0	34.4	30.1	19.8	0.73	1.08	0.95	0.83	0.55	0.664	0.077	0.035	3.51
Powerton/840	August		18.8	27.6	26.1	21.5							(1.70)			
	annual (1973)	18.5	12.6	18.0	15.7	14.0	14.0	0.68	0.97	0.85	0.76	0.76	0.689	0.046		2.40

[a] Based on material balance evaporation

QH - Marciano and Harbeck model (Lake Hefner)
QC - Harbeck et al. model (Lake Colorado City)
QM - Meyer model
QB - Brady et al. model
HN - Harbeck nomograph plus pan evaporation

TABLE 4.5. REGIONAL COMPARISON OF COOLING SYSTEM EVAPORATION RATE[1]

Water Resource Region	Plant	Cooling System[a]	Plant Size (MW)	Capacity Factor	Model Predicted/ Material Balance Evaporation[b,c] (m^3/min)	Summer Normalized Evap. Rate (m^3/min-MW)	Summer Normalized Evap. Rate ($m^3/10^6$ Kcal)	Annual Normalized Evap. Rate (m^3/min-MW)	Annual Normalized Evap. Rate ($m^3/10^6$ Kcal)
Lower Colorado	Huntington	T	400	80	12.8/12.5	—	—	0.04	1.88
	Navajo	T	750	100	13.8/12.6	0.018	1.68	—	—
	Cholla	P	120	0.7	6.3/6.9[α]	0.103	5.81	0.075	3.70
Texas Gulf & Rio Grande	Newman-Unit 1	T	86	59	3.7/4.2	0.072	2.08	—	—
	Newman-Unit 2	T	90	86	3.9/4.0	0.024	2.00	—	—
	Newman-Unit 3	T	110	98	4.5/4.5	0.025	1.86	—	—
	Rio Grande-Unit 6	T	50	30	2.4/1.1	0.292	5.73	—	—
	Rio Grande-Unit 7	T	50	58	2.1/1.4	0.075	3.17	—	—
	Rio Grande-Unit 8	T	165	48	6.5/4.2	0.101	3.96	—	—
	North Main	T	85	100	2.9/2.5	0.034	1.89	—	—
	Permian	T	100	—	3.1/3.0	0.031	1.54	—	—
	Morgan Creek	L	102	12	20.5/20.9[δ]	0.29	11.1	0.201	7.60
South Atlantic Gulf	H.B. Robinson	L	885	67	40.2/44.6	0.089	4.4	0.068	3.31
	Lake Bellows	L	2,286	66	58.7/90.2[β]	0.062	3.5	0.039	2.19
Upper Mississippi	Clay-Boswell	T	350	93	8.4/7.95[d]	0.026	1.35	—	—
	Koshkonong	T	900	100	42/40	—	—	0.04	1.50
	Kincaid	L	1,319	34	34.4/36.2[β]	—	—	0.077	3.51
	Powerton-Unit 5	P	840	47	8.0/18.5[α]	—	—	0.046	2.40
Ohio Mid-Atlantic	Homer City	T	664	57	25.9/39.5[d]	0.036	1.68	0.03	1.40
	Mt. Storm	L	1,662	55	—	0.012-0.026	0.66-1.5	—	—

a Cooling Tower (T); Cooling Pond (P); and Cooling Lake (L).

b For cooling towers the Leung and Moore model was used. For cooling ponds, the Harbeck-Koberg-Hughes; or Meyer model; or the Harbeck nomograph was used dependent upon which model more closely approximates material-balance values.

c Annual values are shown, except for performance test results on cooling towers which are based on full capacity test.

d Summer value

α Harbeck-Koberg-Hughes model

β Meyer model

δ Harbeck nomograph

SECTION 5

SUMMARY OF UE&C REPORT: NONWATER QUALITY IMPACTS OF CLOSED-CYCLE COOLING SYSTEMS AND THE INTERACTION OF STACK GAS AND COOLING TOWER PLUMES

GENERAL DESCRIPTION

The objective of the subject study was to collect, analyze and correlate the information available since 1973 on the following topics: a) the environmental impacts on biota of drift from evaporative saltwater or brackish water cooling towers, b) the impacts of cooling tower plumes on weather, and c) the environmental impacts of the interaction of cooling tower plumes with the combustion gases emitted from the stacks.

The air emitted from a wet cooling tower is characterized by a water vapor plume exiting the top of the tower. This thermally buoyant plume typically contains 1 to 3 percent of the water circulating through the cooling tower. In general, it is a visible plume which can rise to several times the height of the cooling tower depending on the prevailing meteorological conditions. When appropriate meteorological conditions exist, the plume may cause an increase in the frequency of ground level fogging.

The direct contact process of heat transfer in a wet cooling tower allows macroscopic droplets of condenser cooling water to become entrained in the air flowing out of the tower. These droplets, commonly referred to as drift, begin to fall to the ground once the plume leaves the tower. During winter, these droplets can freeze on the surfaces of nearby structures and transportation corridors. Since the drift droplets contain the same chemical constituents as the water circulating through the tower, their presence in the atmosphere may also have significant environmental consequences.

The presence of wet cooling towers, especially large hyperbolic natural draft cooling towers, at fossil fuel-fired steam electric generating stations raises the possibility that the cooling tower plumes will interact with the combustion gases emitted from the station's smoke stacks. The commingling of a cooling tower plume with a stack plume, which contains high concentrations of sulfur oxides, nitrogen oxides and fly ash in addition to carbon dioxide and water vapor, can potentially enhance the formation of acid mist in the atmosphere, causing adverse environmental impacts.

COOLING TOWER DRIFT AND ITS ENVIRONMENTAL IMPACTS

A major concern of using saltwater and brackish water cooling towers is

whether the drift from these towers will produce significant adverse environmental impacts, especially to the biota in the vicinity of the towers. An assessment of the potential environmental impacts on biota should include a determination of the following items:

1. The naturally occurring salt deposition rates and the atmospheric salt concentrations in the vicinity of the cooling tower.

2. The total salt deposition rates and the atmospheric salt concentrations that result when the cooling tower is in operation.

3. The salt concentration levels in vegetation before and after the cooling tower is in operation.

4. The salt tolerance of each indigenous species of the biota.

5. The cumulative effects of salt load on biota.

The available information concerning the aforementioned items was compiled and evaluated in the UE&C study(1). While the UE&C study reviewed all available information, an emphasis was given to the available field studies. A summary of these field studies is described below.

Cooling Tower Drift and Deposition Rate Measurements

The available field studies include: (a) the B. L. England Station of the Atlantic City Electric Company, (b) the Chalk Point Station of the Potomac Electric Power Company, and (c) the Turkey Point Station of the Florida Power and Light Company.

B. L. England Station, Unit 3 --

The B. L. England Station is located near Marmora, New Jersey on the Great Egg Harbor Bay and about 4.5 miles from the Atlantic Ocean. The station has two coal-fired units and one oil-fired unit with a generating capacity of about 160 MWe for each unit and a total station generating capacity of 476 MWe. The oil-fired Unit 3 is cooled by a closed-cycle cooling tower system which employs a hyperbolic counterflow natural draft cooling tower designed and built by Research-Cottrell. The tower has a base diameter of 180 feet and a height of 208 feet. The design circulating water flow rate is 200,000 gpm, and the concentration of total dissolved solids in the circulating water ranges from 24,000 to 32,000 ppm.

Field measurements of drift rate were conducted by the tower manufacturer. The mean drift rate from 15 measurements was 0.000424 percent of the circulating water flow rate with a standard deviation of 0.000123 percent.

Field measurements of atmospheric salt concentration and drift deposition rate were conducted by Environmental Systems Corporation(2,3). Two studies were undertaken during two consecutive years. The first study performed measurements during the year when the tower was not in operation, and the second study performed measurements during the year when the tower was in

operation. The measured results are presented in Figures 5.1 through 5.3(4,5).

Although the field data collected at the B. L. England station and shown in Figures 5.1 to 5.3 indicate that the saltwater cooling tower increases the atmospheric salt concentration and deposition rate, anamolies exist, indicating uncertainties with regard to the effects of the cooling tower. For instance, during the periods when the cooling tower was in operation, the annual average salt deposition rates measured at every sampling location increased relative to those measured during the pre- and operational periods. However, the annual average salt concentrations at these sampling locations did not show a similar increase when the cooling tower was in operation. Possible explanations of this apparent anomaly include: (a) the differences in meteorological condition between the periods (1973-1974 and 1974-1975) when the pre-operational and operational measurements were conducted, or (b) the difference in sampling times for the deposition rate measurements (approximately 24 hours) and the salt concentration measurements (approximately several hours), and (c) "blow-through" occurred when high winds swept through the cooling tower basin carrying with them droplets of the circulating water.

Chalk Point Station, Unit 3 --

The Potomac Electric Power Company's Chalk Point Station is located at the confluence of the Patuxent River and Swanson Creek, about 40 miles southeast of Washington, D.C. The station has three operational units with a total generating capacity of 1329 MWe. Units 1 and 2 are coal-fired base load units with once-through cooling. Unit 3, on which the Chalk Point Cooling Tower Project (CPCTP) has been conducted, is an oil-fired cycling unit. The unit is cooled by a closed-cycle system using a crossflow natural draft cooling tower designed by the Marley Company. The cooling water for this system is taken from the discharge of the once-through cooling for Units 1 and 2 and the flow rate is 260,000 gpm. The salinity in the circulating water ranges from 14,000 ppm to 21,000 ppm during summer. The tower has a base diameter of 374 feet and a height of 400 feet. The Chalk Point Cooling Tower Project is an on-going and the most comprehensive study to date of cooling tower drift and its environmental effects. Summarized are the tests and results obtained so far.

Aircraft traverses through and around the cooling tower plume were conducted using chemical film samplers(6). The drift droplet distribution from two of the traverses is presented in Figure 5.4. Since the chemical film sampler collection efficiency for droplets below 20 microns falls quickly, the histogram shown is only representative of those drift droplets which readily fall out of the plume because of their large mass.

Two independent groups (Johns Hopkins University and Environmental Systems Corporation) measured the cooling tower drift at ground level. The two sets of deposition rate measurements differed by factors of 5 to 10 for the same distances from the cooling tower. Droplets less than 100 microns were not necessarily recorded although they were observed. The explanation of this difference in deposition rates may also lie in the fact that one of the studies was performed under slightly stable conditions. A group at Argonne National Laboratory has attempted to use these data to validate mathematical salt deposition models(4,5).

Turkey Point Station --

Florida Power and Light Company's Turkey Point Station is located about 30 miles south of Miami at the shore of Biscayne Bay. It consists of two 430 MWe fossil units and two 730 MWe nuclear units. Condenser cooling of all four units is provided by a closed-cycle salt water cooling canal system. The salinity of the circulating water ranges from 3,000 ppm to 30,000 ppm.

A single cell mechanical draft crossflow tower with improved drift eliminator design was also installed at the station to evaluate the effects of drift from a mechanical draft cooling tower. The tests performed by Hunter(7) indicated that the increase in ambient salt concentrations resulting from the tower operation was less than the instrument accuracy of 3 to 5 ug/m^3.

Field Studies of Biological Impacts of Cooling Tower Drift

At Chalk Point Station and Turkey Point Station, studies have also been conducted to assess the vegetative impacts of salt drift from the cooling towers. The UE&C study found no field study investigating the impacts of salt drift on animal species. The available field studies on vegetative impacts are summarized below.

Chalk Point Station --

A series of studies has been conducted at the station to investigate the cumulative short term effects of salt loading on native vegetation(8-13). Four tree species native to the Chalk Point area have been studied and these are: Virginia pine, black locust, sassafras and dogwood. The test data indicate that the naturally occurring salt loading (Na^+ and Cl^- ions) on the four tree species do not approach the threshold concentrations of these ions when marginal necrosis occurs(8). The threshold concentrations of Na^+ and Cl^- ions for many woody species have been determined by Curtiss et al.(7) to be 2000 ppm for Na^+ ions and 5000 ppm for Cl^- ion. Operational test data obtained in 1975 of the four tree species did not show significant increases of Na^+ and Cl^- concentrations(8). Similar results were obtained for soybeans, tobacco, and corn with regard to the naturally occurring salt loading and the increase in salt concentration resulting from tower operation(9).

Turkey Point Station --

At Turkey Point, Hindawi et al.(14) introduced cultivated plants (bush beans) to the area near the station's saltwater cooling tower. Using glass slide collectors, these workers observed different salt deposition rates on the windward and leeward sides of the plants. The excessive accumulation of Na^+ and Cl^- ions in the tissue on one side of a plant's foliage can result in "molding," i.e., stunted growth on the windward side of the plant(15).

The literature search in the UE&C study found an abundance of information on the effect of salt aerosol deposition on vegetation. But, the results generally cannot be directly applied to power plant cooling towers because the experimental conditions do not necessarily correspond to power plant environments.

Conclusions

Based on the information compiled, the following major conclusions have been drawn concerning the measurements and the biological impacts of drift from saltwater and brackish water cooling towers.

1. Cooling tower drift and salt deposition apparently do not increase ambient salt loading to the extent that a significant impact has been observed or is expected. Field data from the operational Chalk Point and B. L. England Stations indicated that although drift and its deposition from cooling towers may be significant within the immediate region of the station, contributions from cooling towers beyond one kilometer may be inseparable from the natural salt loading of the local region.

2. The degree of salt injury to biota from cooling tower drift and salt deposition cannot be firmly determined using presently available data.

WEATHER MODIFICATIONS BY EVAPORATIVE COOLING TOWERS

The atmospheric effects of evaporative cooling towers operating at steam electric generating stations include the potential modification of the weather locally with respect to the following areas: (a) the frequency and intensity of fogging and icing conditions, (b) the enhancement of cloud formation, and (c) the enhancement of precipitation. The information compiled is summarized below.

Fogging and Icing

Fogging and icing, as phenomena resulting from visible, wet cooling tower plumes travelling near ground level, have been observed during cooling tower operation. Meteorologists have derived various mathematical models to predict the frequency of occurrence of fogging and icing from wet cooling tower operation, and these models have been summarized in a model validification effort performed by the Argonne National Laboratory(4,5). Although the model predictions differ, they do indicate that fogging and icing are not likely to occur beyond a 10-kilometer radius of the cooling tower(4,5).

Field observations of fogging and icing conditions near wet cooling towers have been reported in the literature. These include the studies by Slawson et al.(16), Kramer et al.(17), and Woffinden et al.(6). Slawson et al. noted that no ground fog from the operation of a natural draft cooling tower at the Paradise Station of the Tennessee Valley Authority was observed during a five-year study. Kramer et al. also found no evidence of induced ground fogging from the natural draft cooling towers at the John E. Amos Power Station of the American Electric Power Service Corporation.

The occurrence of icing rather than fogging is due to the presence of temperatures below the freezing points of the water vapor and drift droplets in the cooling tower plume. Meteorological conditions conducive to fogging include wind speeds greater than two meters per second, stable temperature

lapse rates, relative humidity greater than 95 percent, and low dry bulb temperatures. These conditions create downwash, low dispersion, low evaporation, and condensation.

From field studies, Slawson et al.(16) determined that icing from the natural draft cooling towers at the Paradise Station was insignificant. At the Chalk Point Station, Woffinden et al.(6) found that the natural draft cooling tower caused no more than a few millimeters of ice on the structures located on the plant site. Kramer et al.(17) reported that only in rare instances could icing be observed at distances more than five kilometers from a natural draft cooling tower.

Cloud Enhancement

The meteorological conditions which are conducive to the formation of additional clouds include a stable stratification of the vertical temperature profile, high relative humidity, cool temperatures, and low insolation. Under these conditions the clouds will be typically of the stratus variety.

Theoretical considerations indicate that wet cooling towers can modify these natural cloud formations(17,18,19). However, there have been no field studies to establish the extent of any cloud enhancement.

Precipitation Enhancement

Kramer et al.(20) measured a maximum of 2.5 centimeters of snowfall from natural draft cooling towers at the John E. Amos Station when no other precipitation existed in the area. Snow accumulations were found as much as 43 kilometers from the cooling tower, and visibility was restricted to less than 1600 meters in the area where the cooling tower plumes approached ground level. However, Martin(21) did not find any statistically meaningful change in rainfall near a 2000 MW electric generating station with eight natural draft cooling towers in England. Convective precipitation enhancement by wet cooling towers has not been observed with the exception of the observations noted by Selvan et al.(22).

Conclusions

The following conclusions have been drawn concerning weather modification by evaporative cooling towers.

1. Field observations on the fogging and icing from natural draft cooling towers suggest that these effects are not significant environmental problems. At most, only a few millimeters of ice have been observed to accumulate on surrounding structures, while fogging from natural draft towers has not been observed under a variety of meteorological conditions. Fogging and icing from mechanical draft towers have been observed, but the tower design significantly affects the probability that the plume will intersect the ground.

2. Precipitation and cloud enhancement by cooling towers have been insignificant although they have been observed in a few

cases. Previous studies have indicated that precipitation and cloud enhancement for any sector downwind from a tower are increased by only a few percent.

COOLING TOWER PLUME AND STACK GAS INTERACTION

The presence of wet cooling towers, expecially large hyperbolic natural draft cooling towers, at fossil fuel-fired steam electric generating stations raises the possibility that the cooling tower plumes will interact with the combustion gases emitted from the stations' stacks. The commingling of a cooling tower plume with a stack plume, containing high concentrations of sulfur oxides, nitrogen oxides, and fly ash in addition to carbon dioxide and water vapor, can enhance the formation of acid mist in the atmosphere. The presence of acid mist may be evident as increased concentrations of aerosols and fine particulates containing sulfates and nitrates in the commingled plume, acid rainfall, and a reduction in atmospheric visibility.

A complete description of the interaction of a cooling tower plume with a stack plume requires an understanding of: (a) the physical, chemical, and geometrical characteristics of each plume as it leaves the source; (b) the meteorological conditions which affect the rise of each plume in the atmosphere and the spatial extent of the interaction of the plume and the ambient atmosphere; and (c) the complex physicochemical reactions that can take place when the plumes commingle. At present, there are insufficient data to give a comprehensive description and quantitative assessment of cooling tower plume/stack plume interactions.

Meteorological conditions conducive to the merging of a visible cooling tower plume with a stack plume have been established reasonably well in the literature. The longer than usual visible cooling tower plumes occur during light winds, high relative humidity (greater than 80 or 85 percent), low ambient temperatures, and stable lapse rates. The light winds and stable lapse rates assure low atmospheric dispersion of the plumes. The high relative humidity reduces the rate of evaporation of the water droplets in the cooling tower plume, thereby enhancing the visible plume length. Finally, the low temperature may also help to keep the water in the cooling tower plume in a condensed state.

Hanna(18) summarized the trend of recent research efforts toward understanding the chemical reactions taking place in turbulent mixtures, but a practical, useful model remains to be developed.

Quantitative data concerning acid precipitation enhancement resulting from plume/stack gas interaction are scarce. Existing literature generally provides unsophisticated explanations and non-quantitative descriptions. Only three field studies, one at the Chalk Point Station(6) and two at the Keystone Station(23,24), obtained limited quantitative data, but these data are site specific and cannot reliably be extrapolated to general circumstances.

Conclusions

The major conclusions concerning cooling tower plume and stack gas

interaction are as follows:

1. There is no mathematical model for predicting acid precipitation or deposition due to cooling tower plume/stack gas interaction.

2. Neither the enhancement of acid precipitation due to cooling tower plume/stack gas interaction nor the quantification of resulting environmental impacts has been demonstrated in the field.

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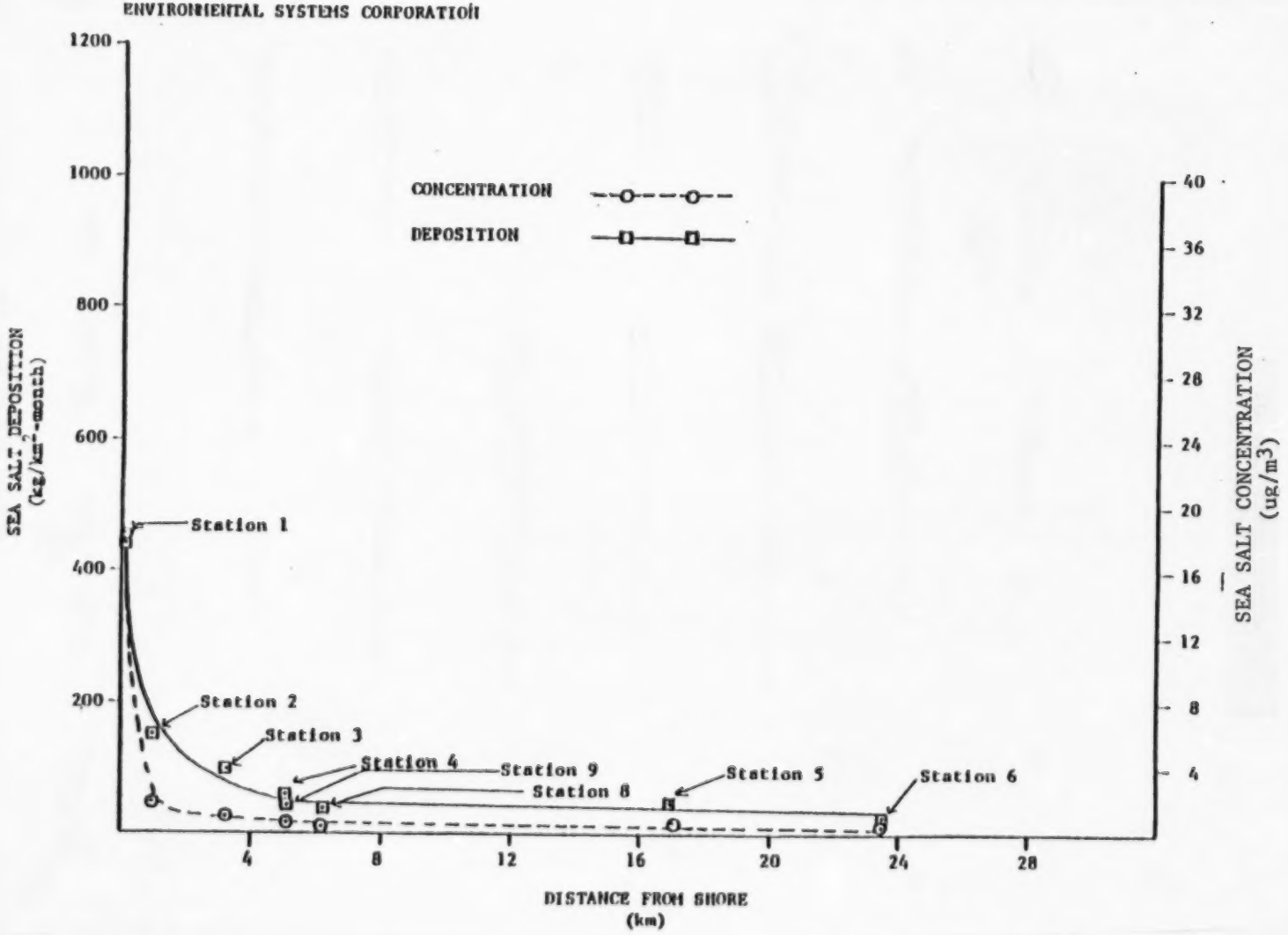

Figure 5.1. Average Sea Salt Concentration and Deposition as a Function of Distance from the Shore (November 6, 1974 - November 11, 1975) (Unit Operation: Off During Entire Test Period)

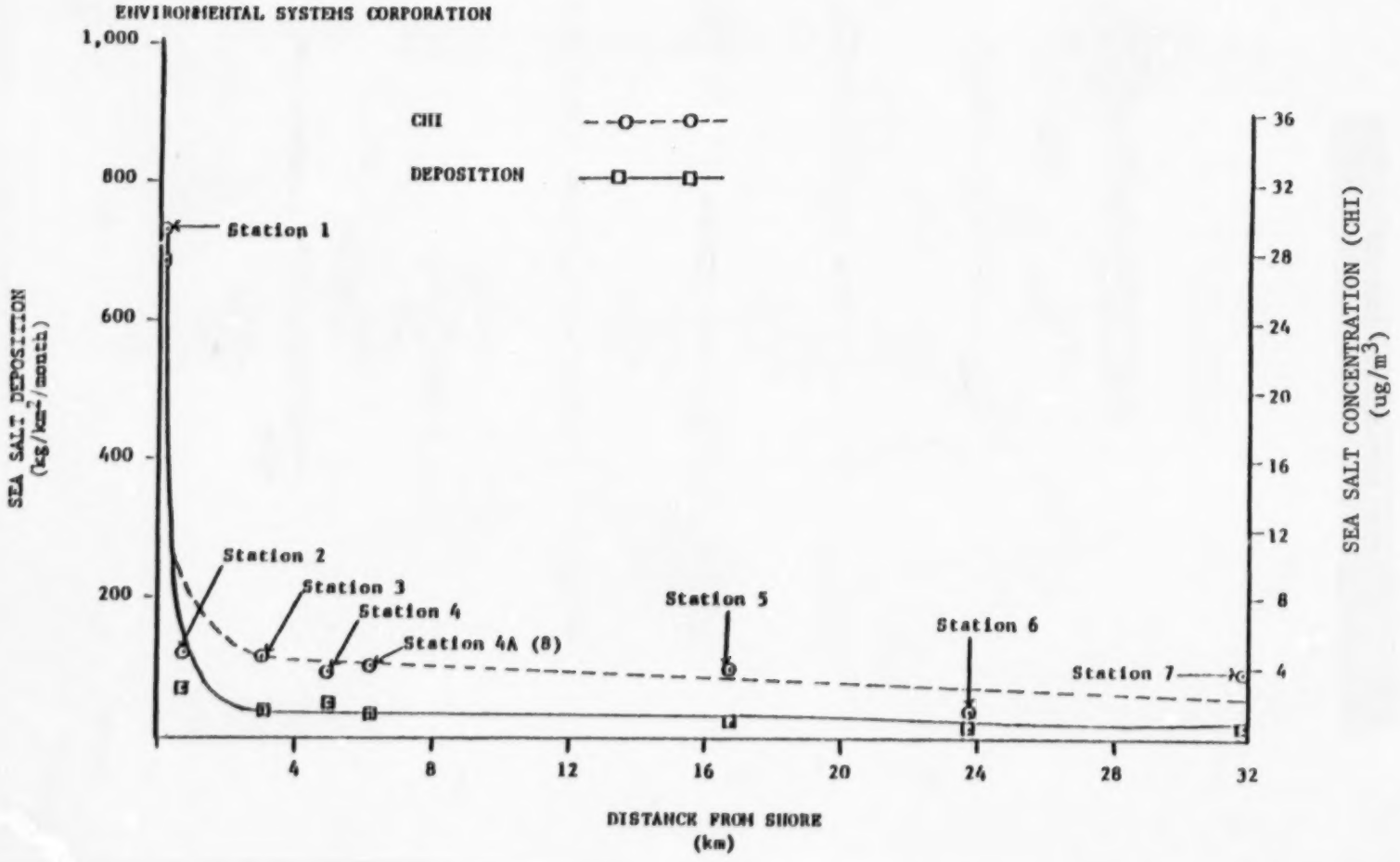

Figure 5.2. Average Ambient Ground Level Sea Salt Concentration and Deposition as a Function of Distance from the Shore (November 20, 1973 - November 5, 1974)

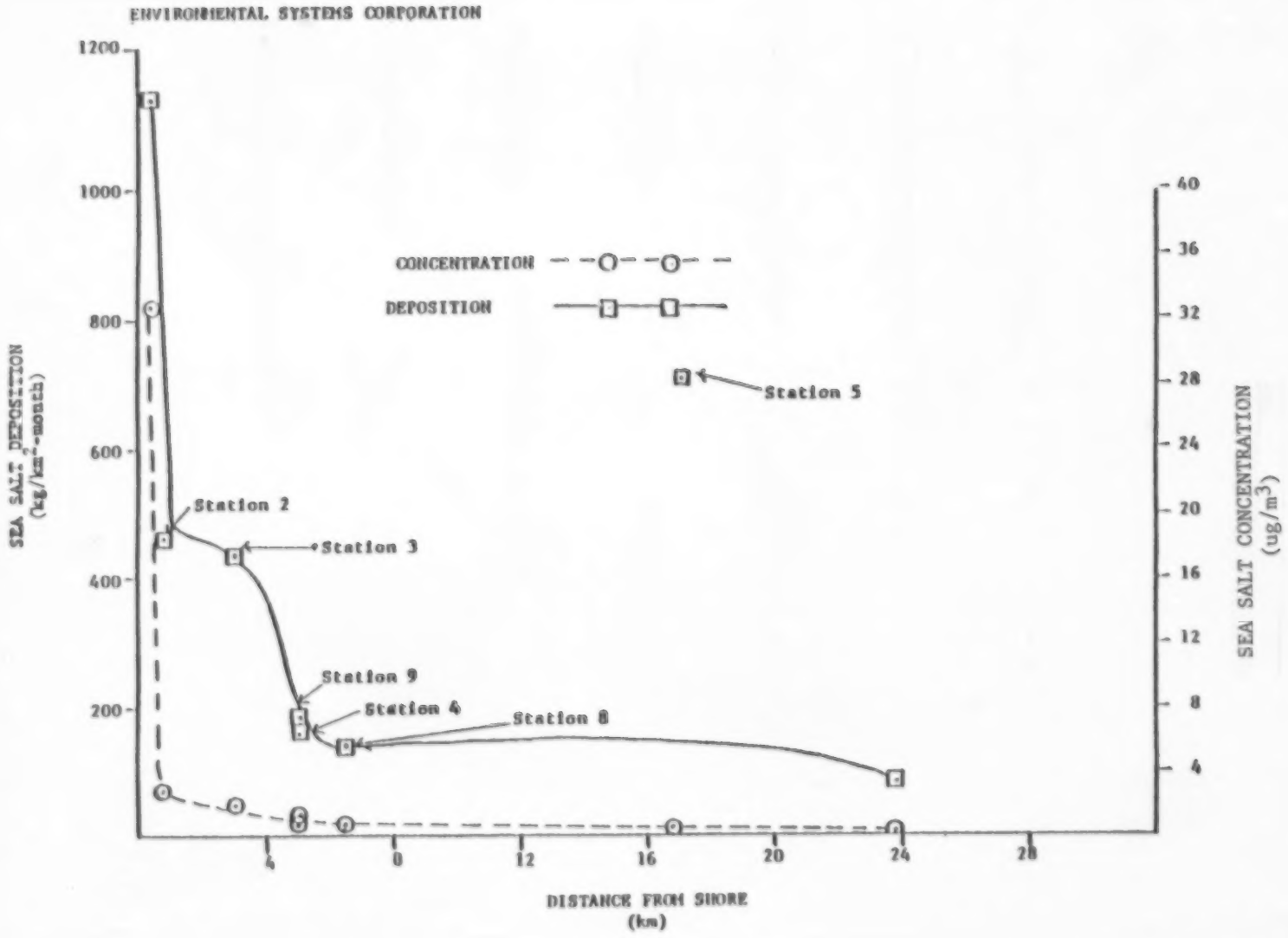

Figure 5.3. Average Sea Salt Concentration and Deposition as a Function of Distance from the Shore (November 6, 1974 - November 11, 1975) (Unit Operation: On During Entire Test Period)

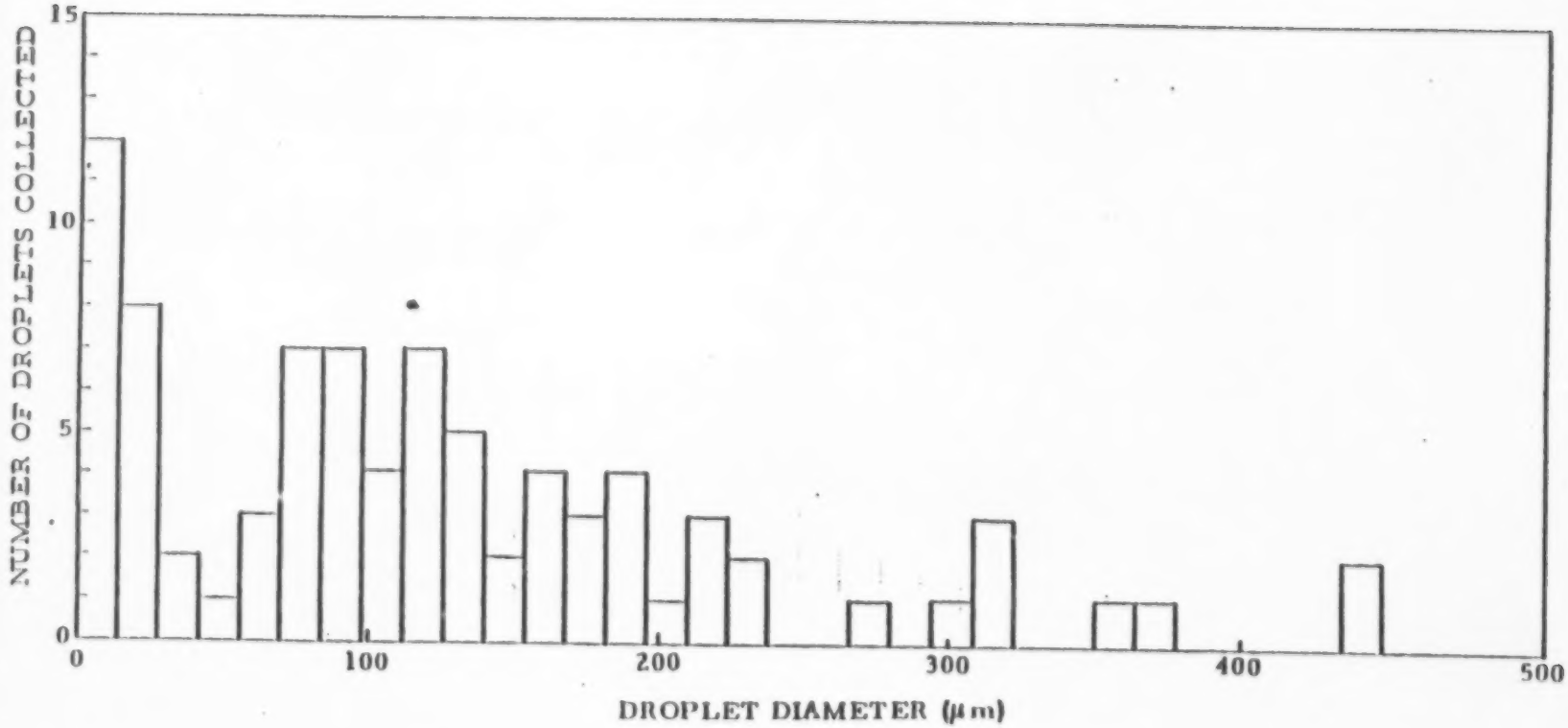

Figure 5.4. Histogram of Droplets Collected by Film Sampler (Traverse 15-8, 15-9)